MSSM Higgs boson searches at DØ

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For the DØ collaboration

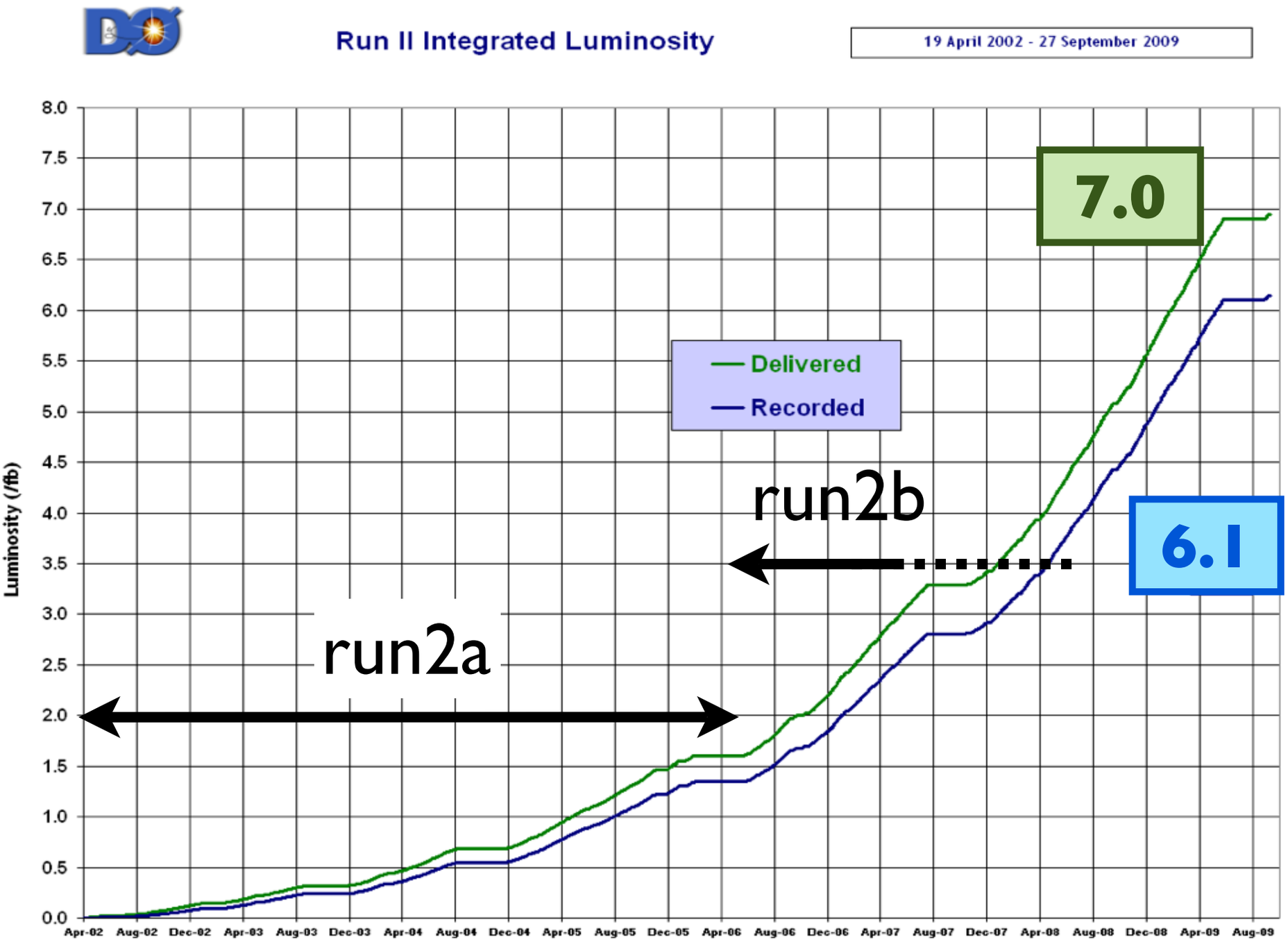
Overview

- Motivations
- Neutral Higgs searches
- Combinations
- Charged Higgs searches
- Prospects
- Conclusions

Fermilab Wine & Cheese
2 October 2009

Available luminosities

Many thanks to the accelerator division!



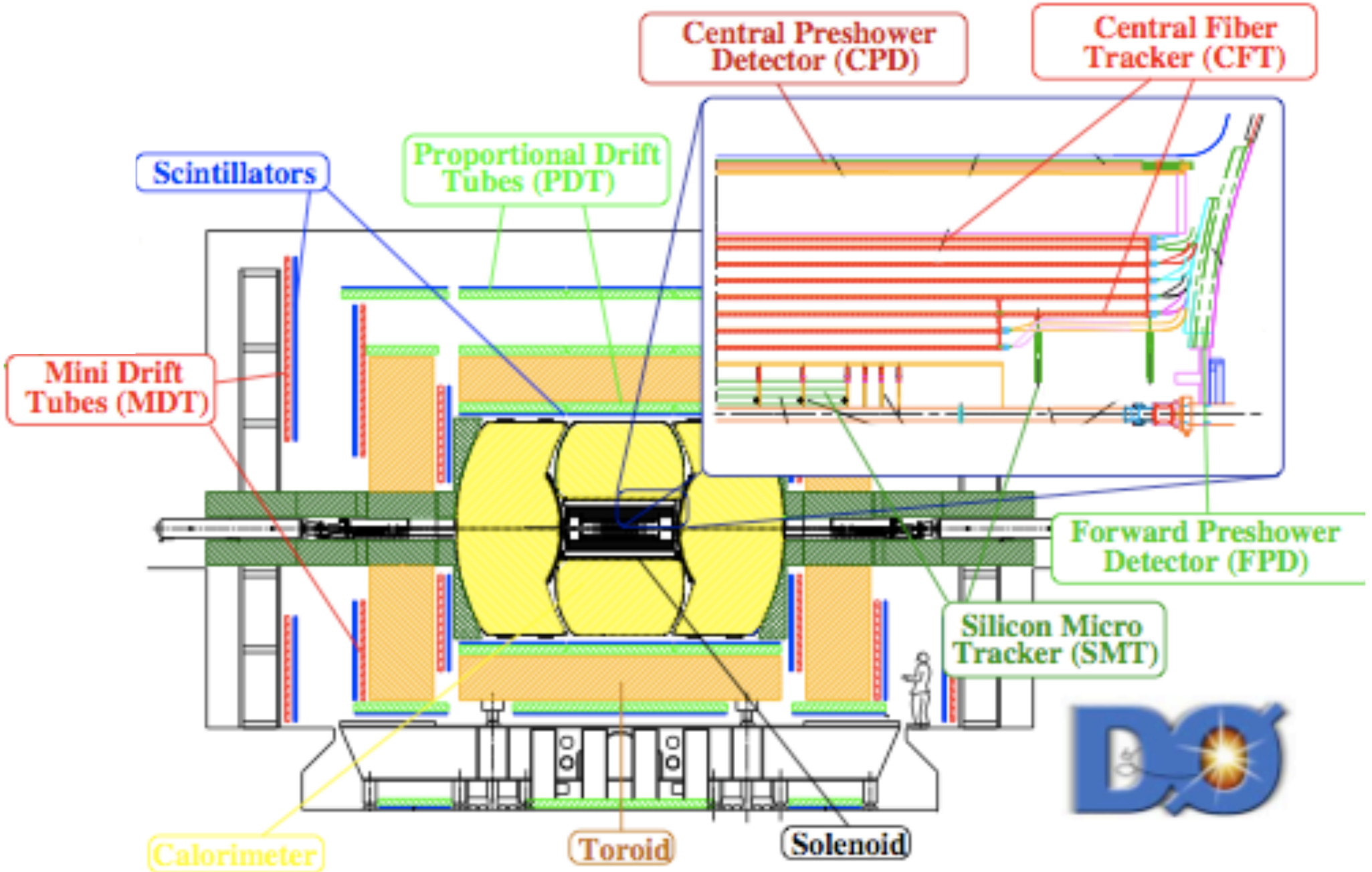
In this talk:

- run2a: 1.0fb^{-1}
- run2b: 1.2fb^{-1}

or 1.7fb^{-1}

Multi purpose detector:

μ id, EM id, jets, taus, $\not\!\!E_T$, b-jets tagging



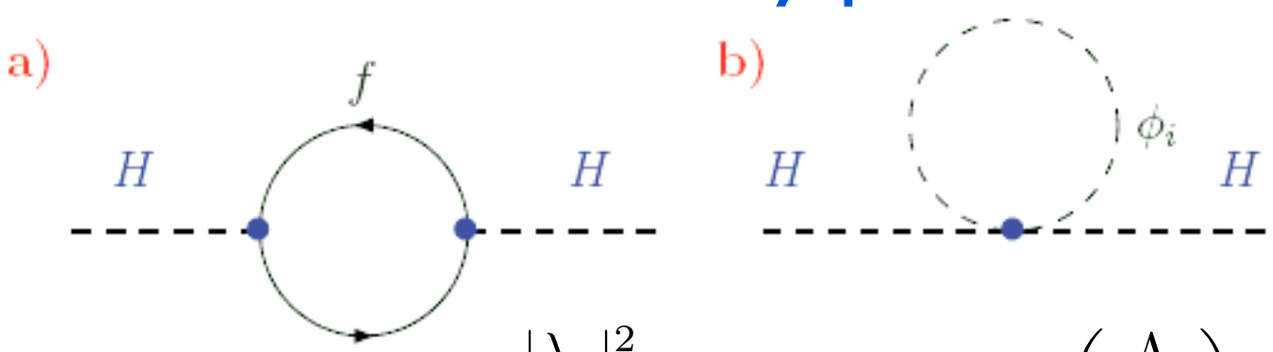
Introducion

SUSY in a nutshell

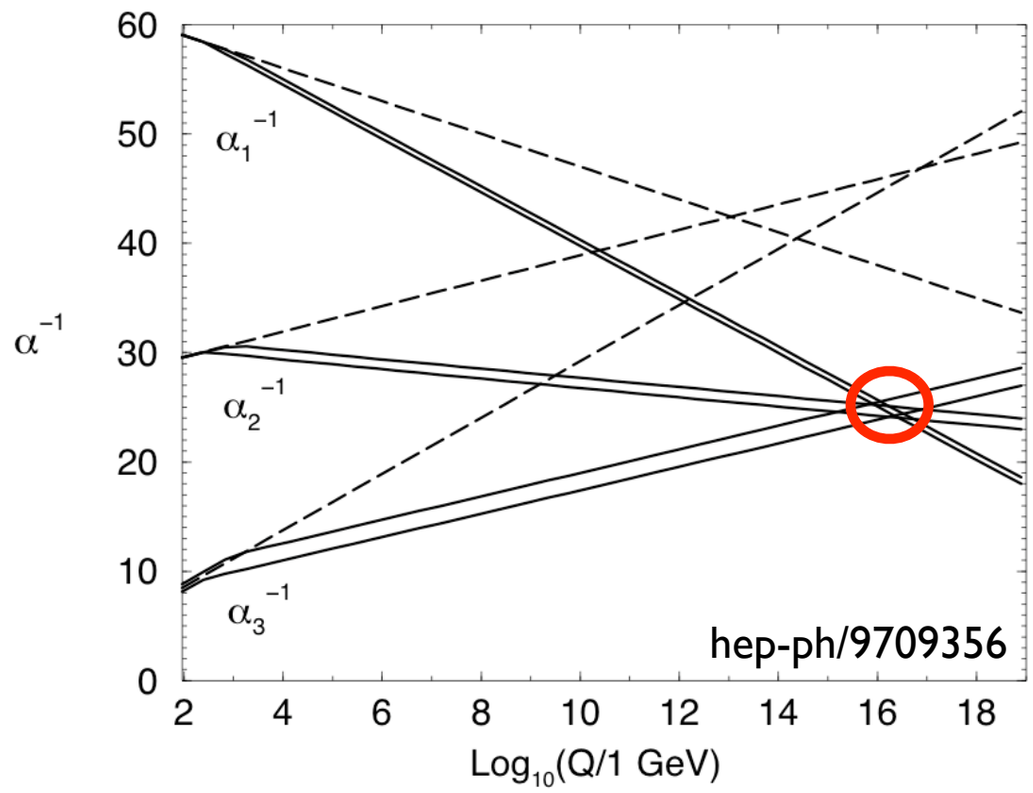
Standard Model very successful but not complete.

Supersymmetry (SUSY) is very popular:

- ✓ extension of Poincaré group: fermions ↔ bosons
- ✓ solves the hierarchy problem

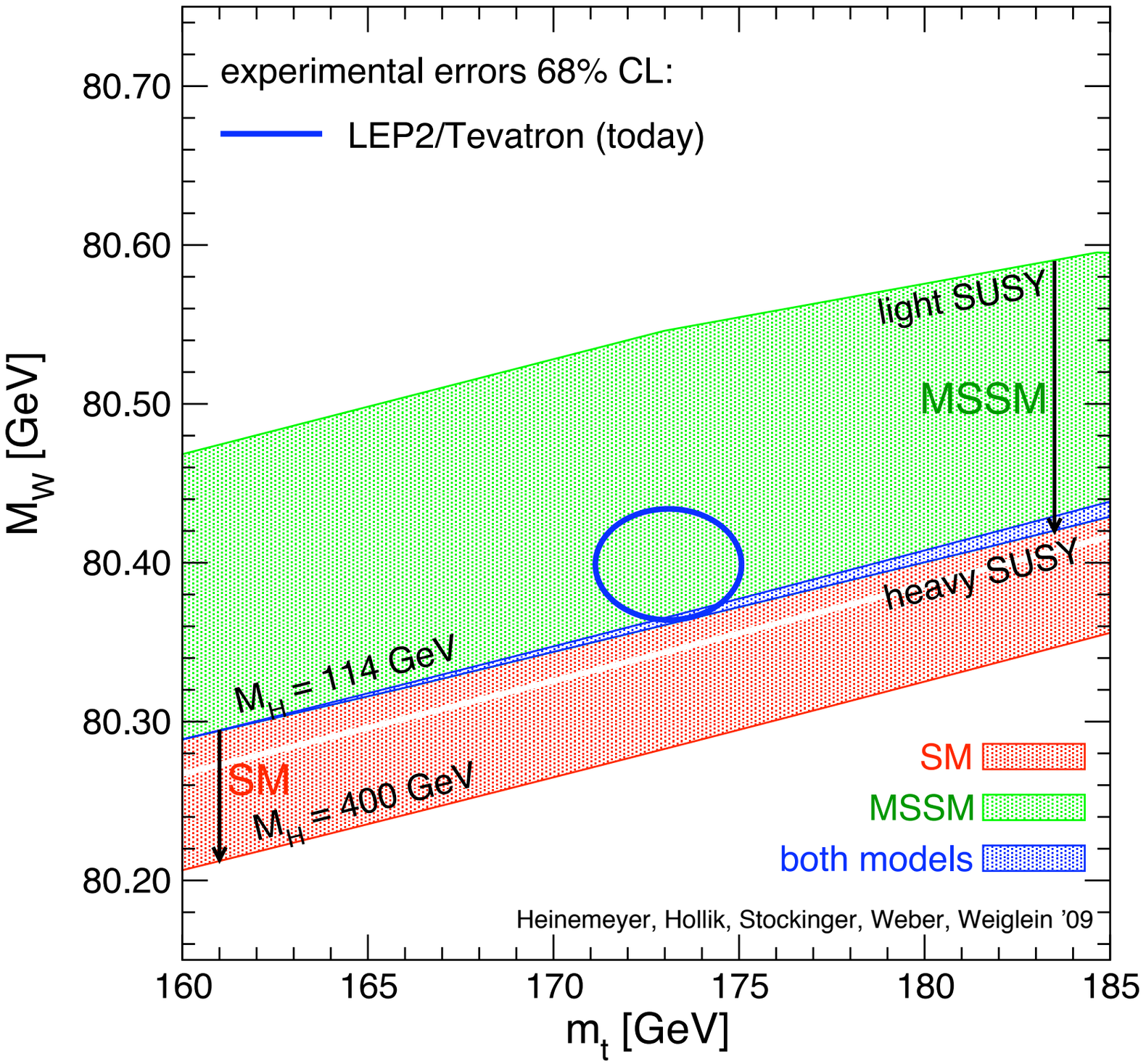


$$\Delta M_H^2 = \frac{|\lambda_f|^2}{8\pi^2} \times (m_f^2 \ominus m_S^2) log\left(\frac{\Lambda}{m_S}\right) + ...$$

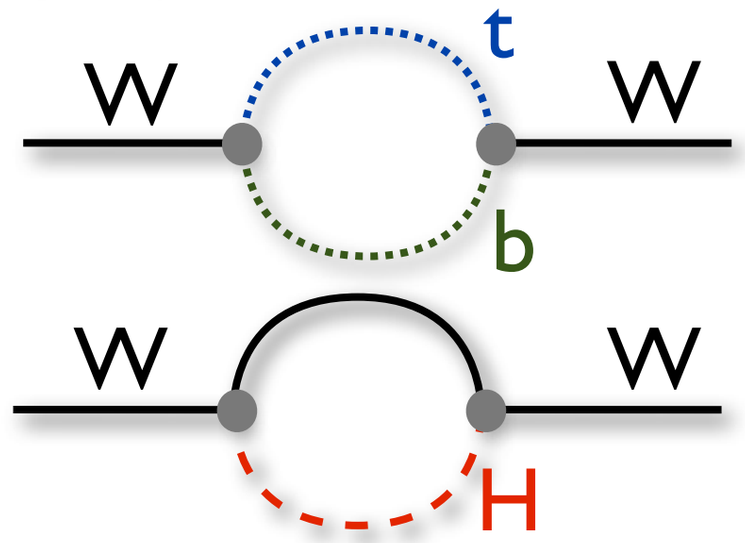


- ✓ unification of the gauge couplings
- ✓ lightest SUSY Particle
  (possible Dark matter candidate)
- ✓ full set of new particles ("s"-particles)
- ✓ broken symmetry
- ✓ s-particles masses must not be too high: TeV scale

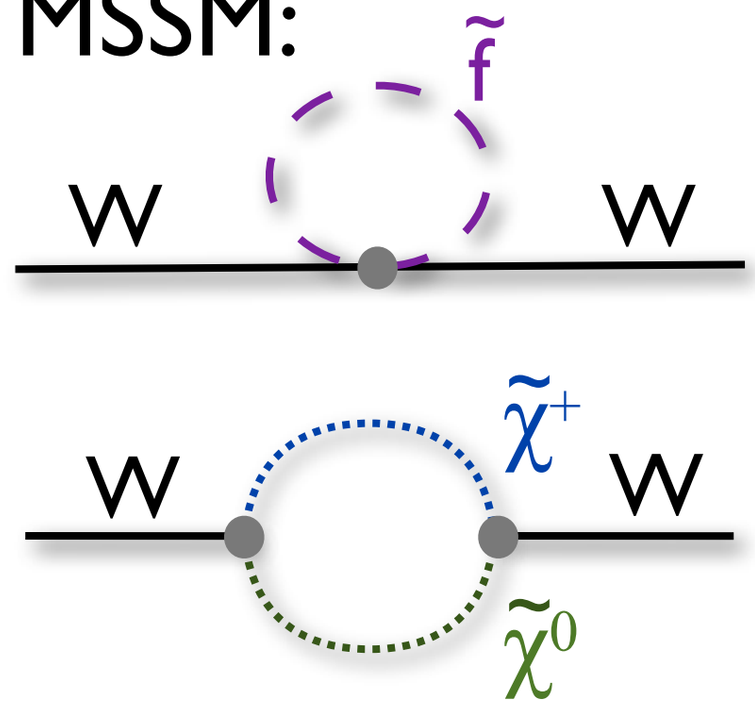
Why looking to the MSSM?



SM:



MSSM:



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Higgs sector in the MSSM

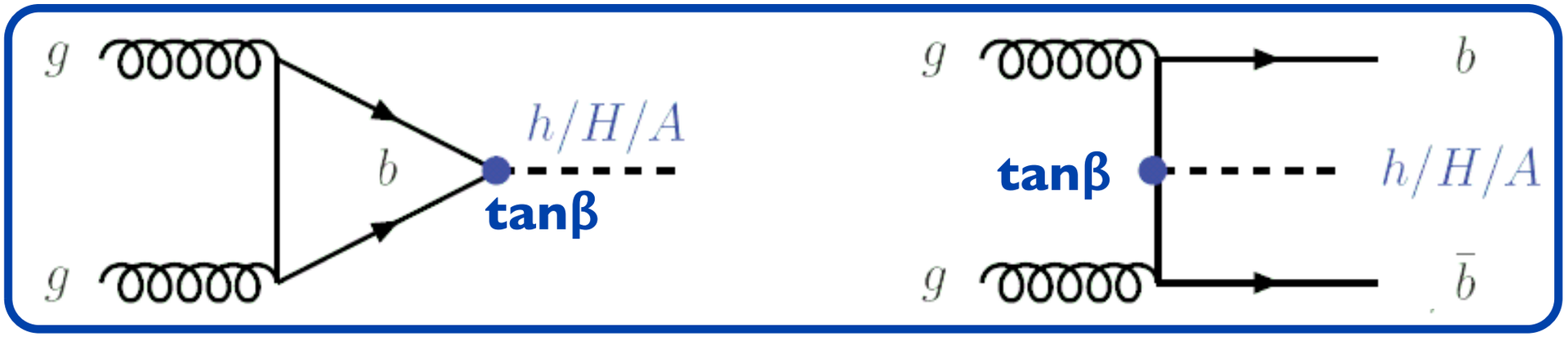
- SUSY requires at least 2 Higgs doublets (super potential structure, triangular anomalies cancelation)
- MSSM exactly 2 Higgs doublets, one couples to down quarks (vev v_d), the other one to up quarks (vev v_u). Important parameter: $\tan\beta = v_u/v_d$

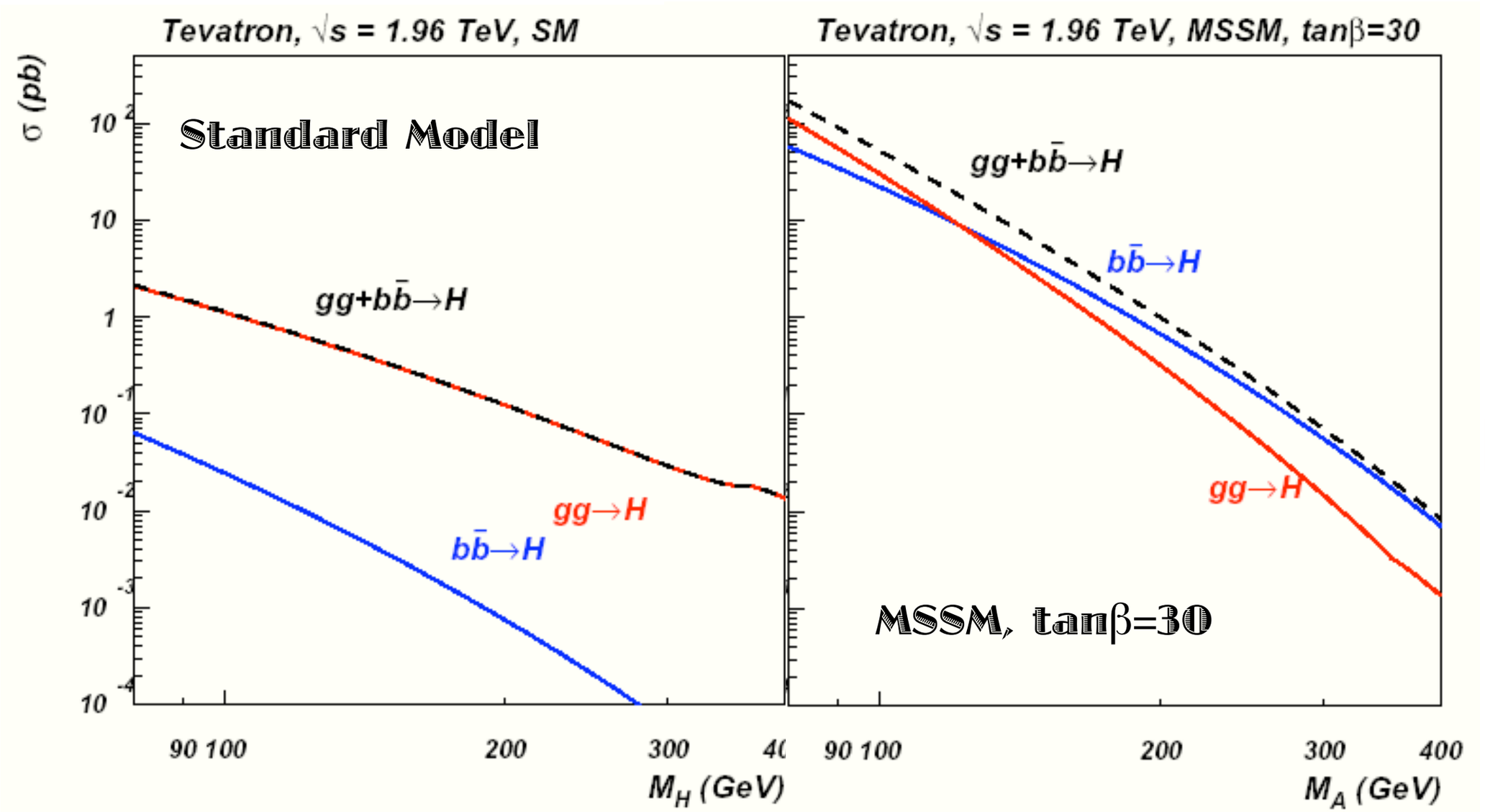
NB: $\tan\beta \sim 35 = m_t/m_b$ is appealing (large $\tan\beta$)

- After EW breaking: 5 physical states
  - 3 neutral Higgs bosons: h/H (CP-even) and A (CP-odd)

    convention: $m_h < m_H$, h/H/A generically denoted Φ
  - 2 charged Higgs bosons: $H^{\pm}$
- At tree level: EW breaking controlled by M_A and $\tan\beta$. Radiative corrections make it more model dependent
- There must be a light Higgs (h) with $m_h \leq 135$ GeV/c^2

Susy Higgs production



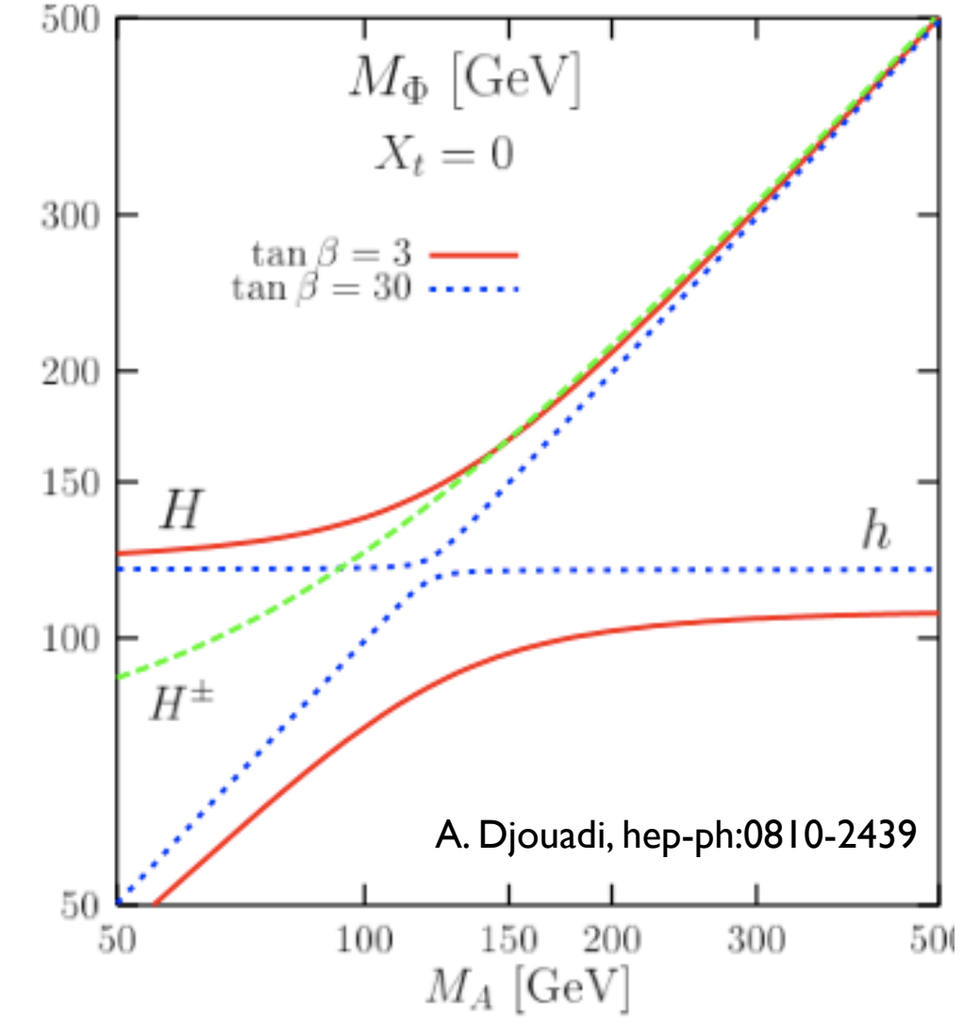


Look for high tanβ!

High tanβ regime

MSSM dedicated Higgs searches at the TeVatron usually takes place in the large tanβ regime:

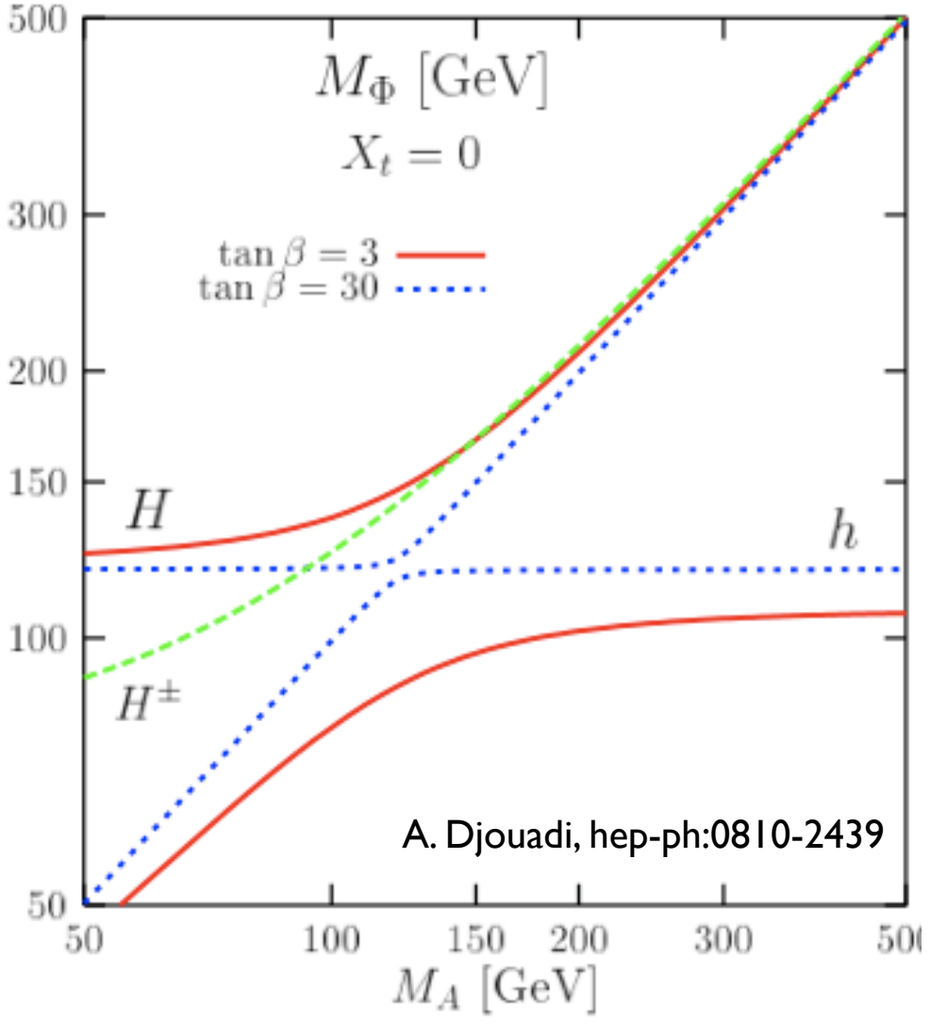
- h/A or H/A are degenerate in mass σ_{prod} x 2!
- coupling to b quarks enhanced by tanβ



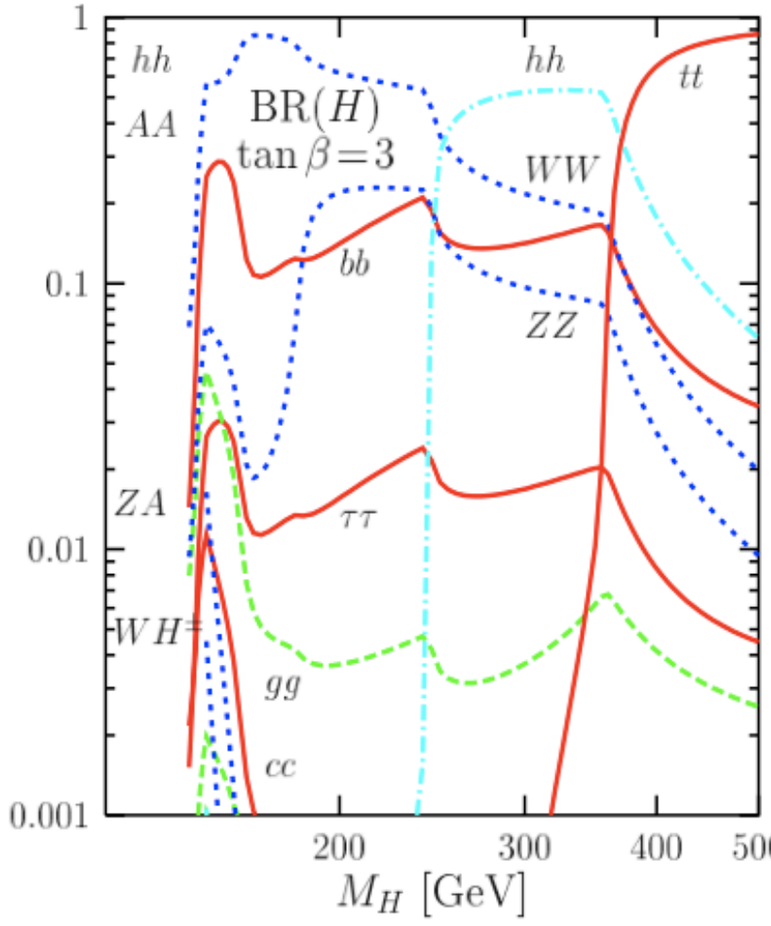
High tanβ regime

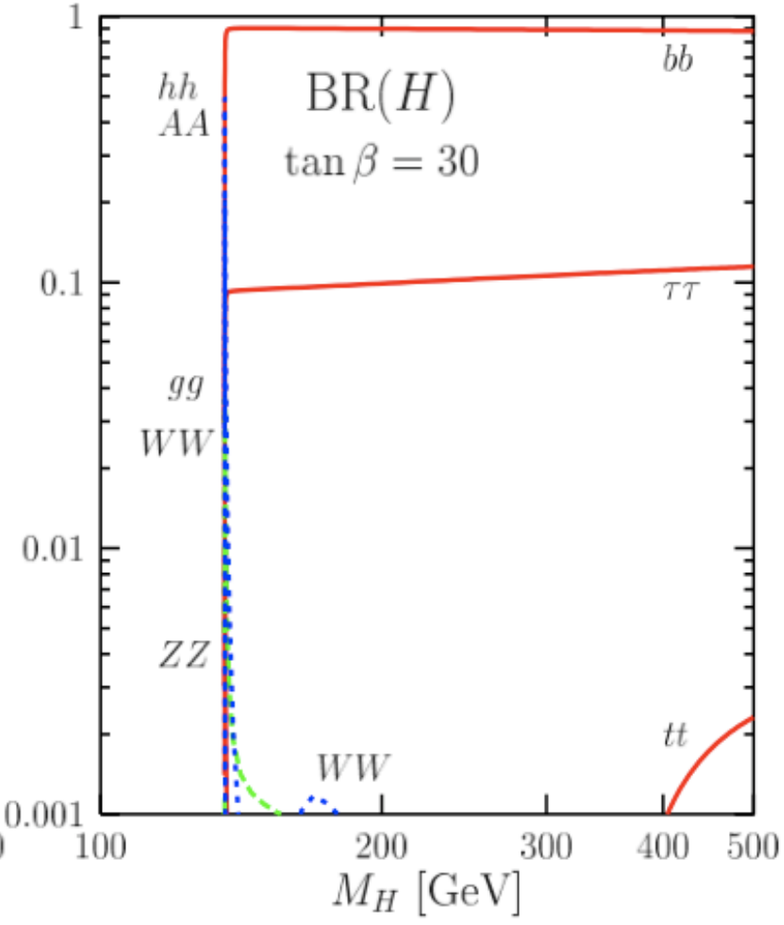
MSSM dedicated Higgs searches at the TeVatron usually takes place in the large tanβ regime:

- h/A or H/A are degenerate in mass σ_{prod} x 2!
- coupling to b quarks enhanced by tanβ
- neutral Higgs: $\mathcal{B}(\phi \to b\bar{b}) \approx 90\ \%$ and $\mathcal{B}(\phi \to \tau^+\tau^-) \approx 10\ \%$
- charged Higgs: if $m_{H+} < m_{top}$: $\mathcal{B}(H^+ \to \tau^+\nu_\tau) \approx 1$



A. Djouadi, hep-ph:0810-2439





A. Djouadi, hep-ph0810-2439

Strategy for limit settings

If data are compatible with background:

1. place limits in a model independent way
2. place limits into 4 different scenarii

   use *FeynHiggs* or *CPSuperH* to get the MSSM cross sections

- m_h^{max} **scenario:**
  - $X_t = 2$ TeV;
  - $\mu = \pm 0.2$ TeV;
  - $M_2 = 0.2$ TeV;
  - $m_{\tilde{g}} = 0.8$ TeV
  - $M_{SUSY} = 1$ TeV

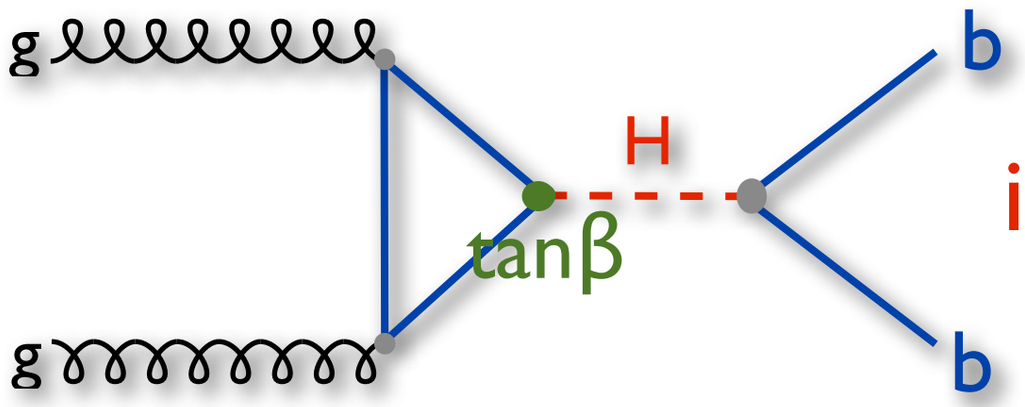
- **No-mixing scenario:**
  - $X_t = 0$ TeV;
  - $\mu = \pm 0.2$ TeV;
  - $M_2 = 0.2$ TeV;
  - $m_{\tilde{g}} = 1.6$ TeV;
  - $M_{SUSY} = 2$ TeV

M. S. Carena, S. Heinemeyer, C. E. M. Wagner, and G. Weiglein, Eur. Phys. J. C 26, 601 (2003).

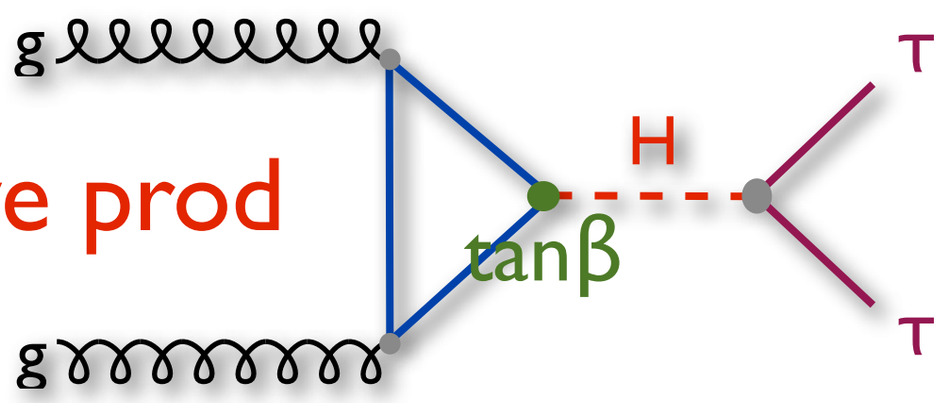
Neutral Higgs searches

What do we search for?

bb channel

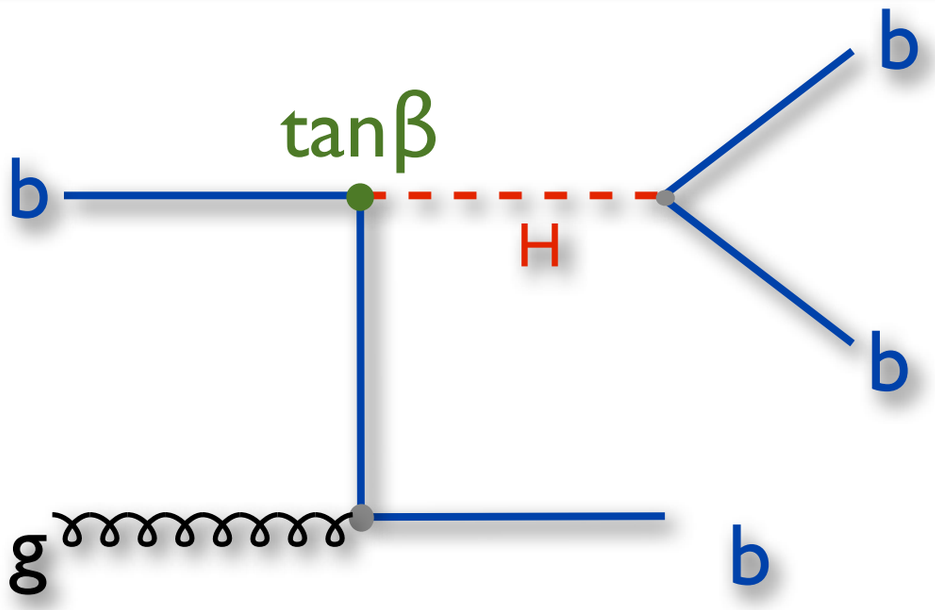


ττ channel



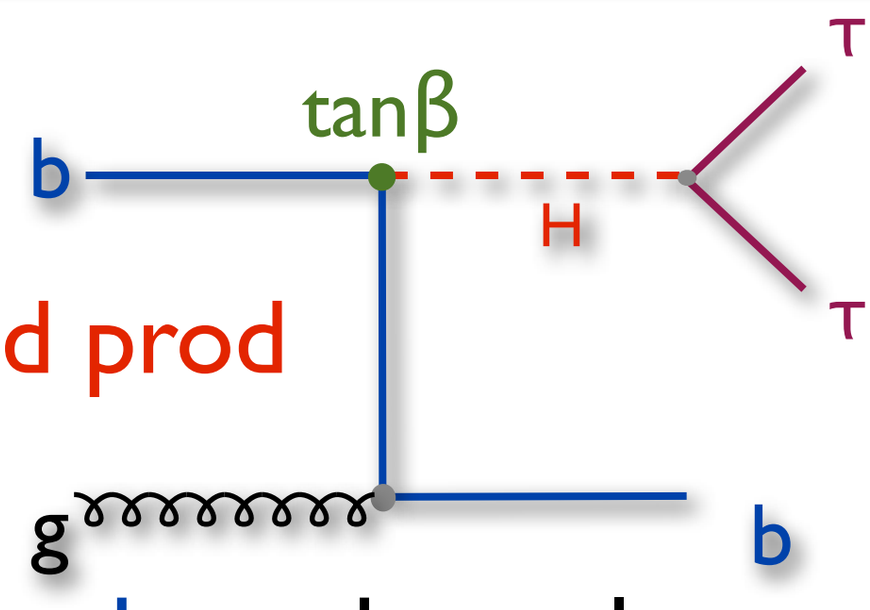
inclusive prod

bbb channel



associated prod

bττ channel



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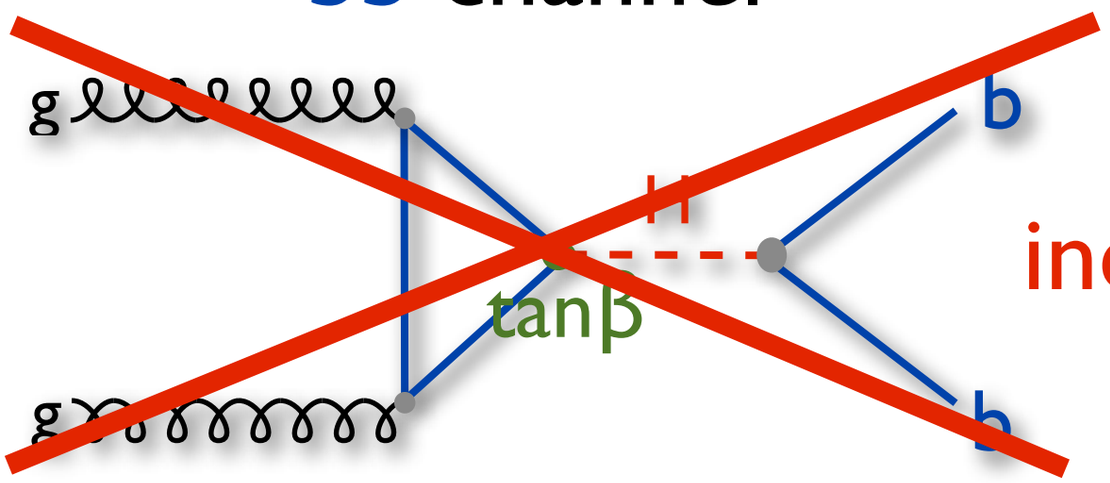
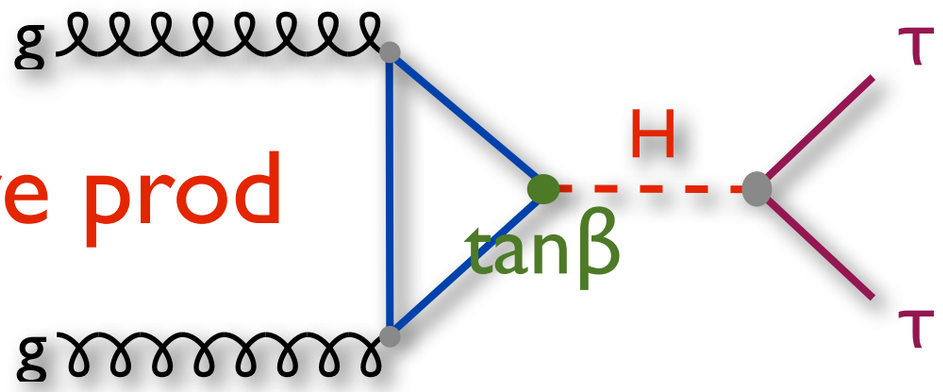
~~bb channel~~



ττ channel



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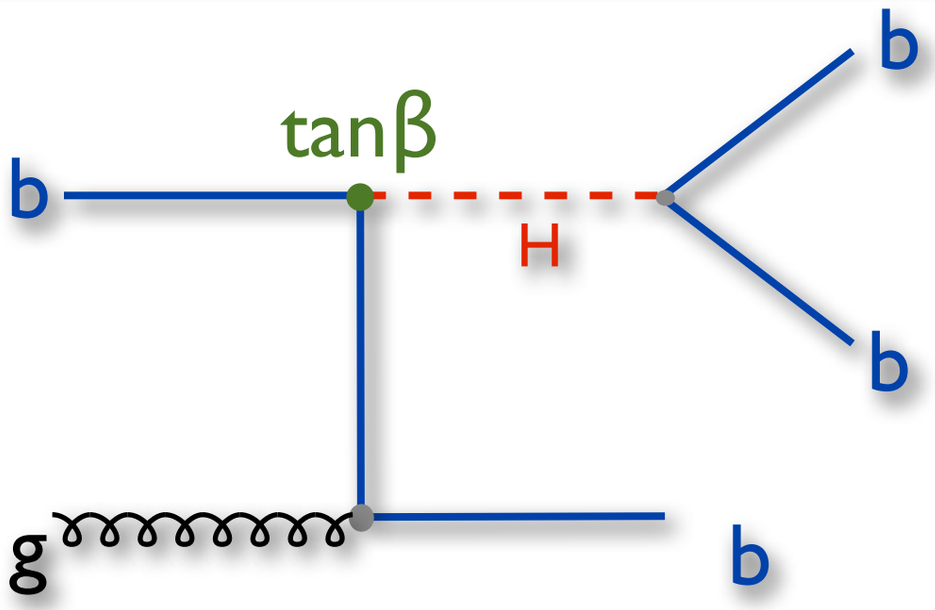
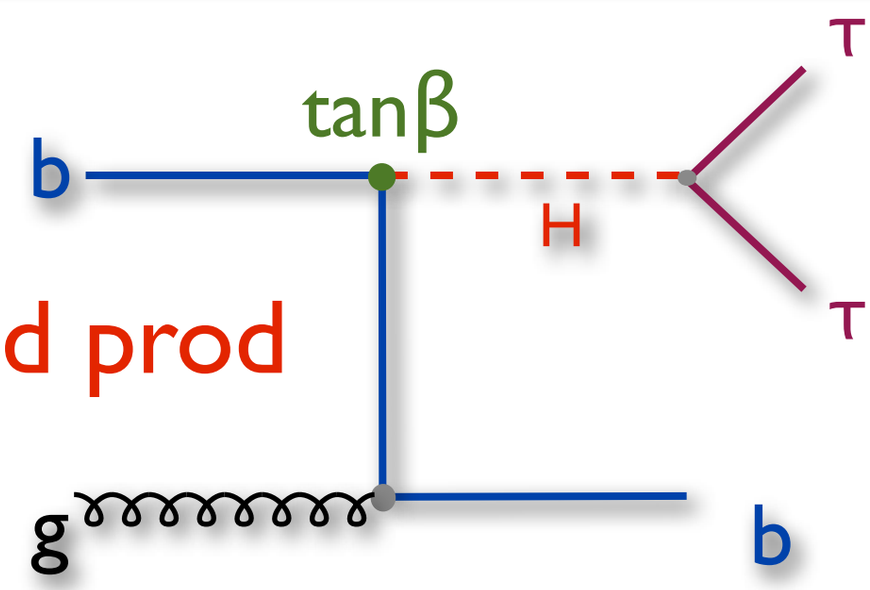
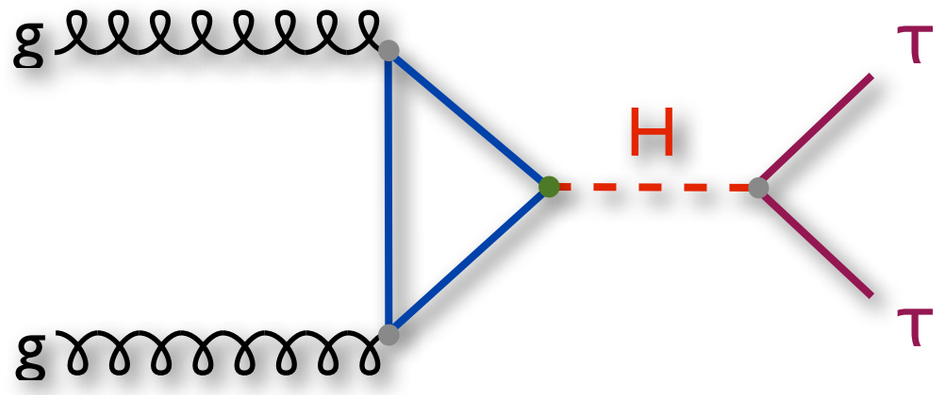


bbb channel



bττ channel

- Inclusive Higgs production: only one channel accessible $\Phi \to \tau\tau$

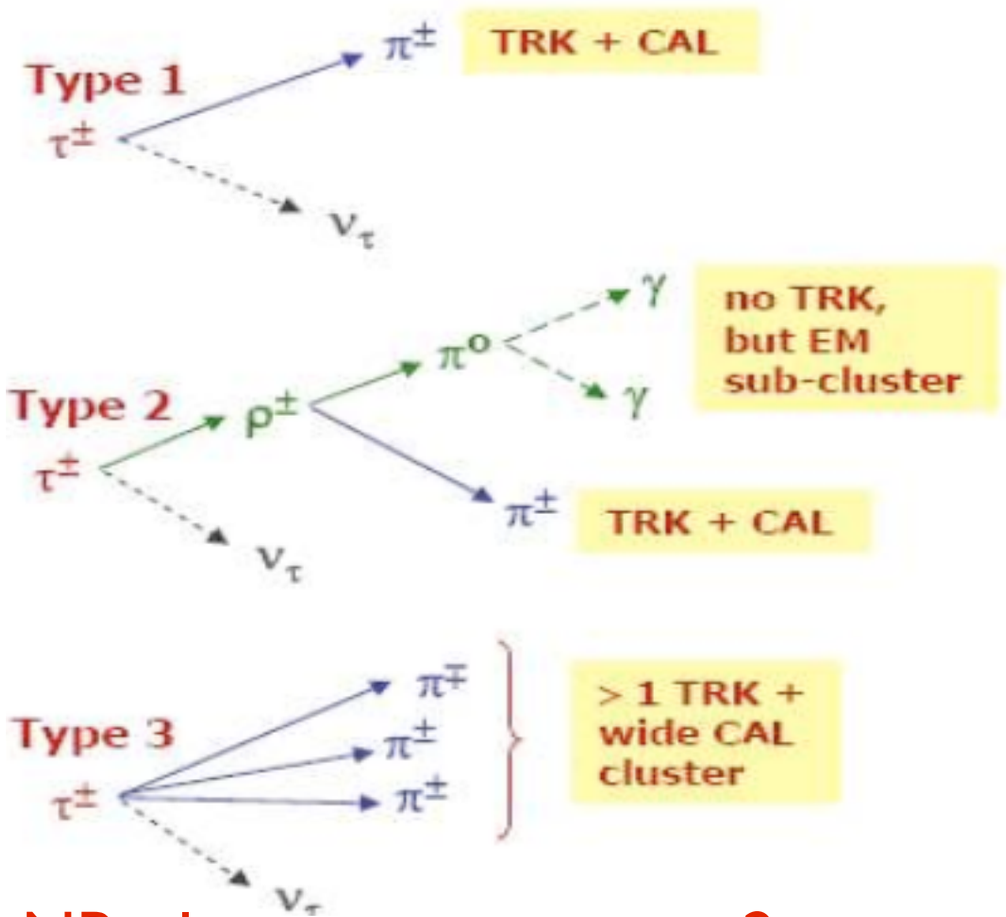


- Challenges: jets mimic hadronic τ decays (largest branching fraction). Need to reconstruct several hadronic τ decays and to combine several sub channels!

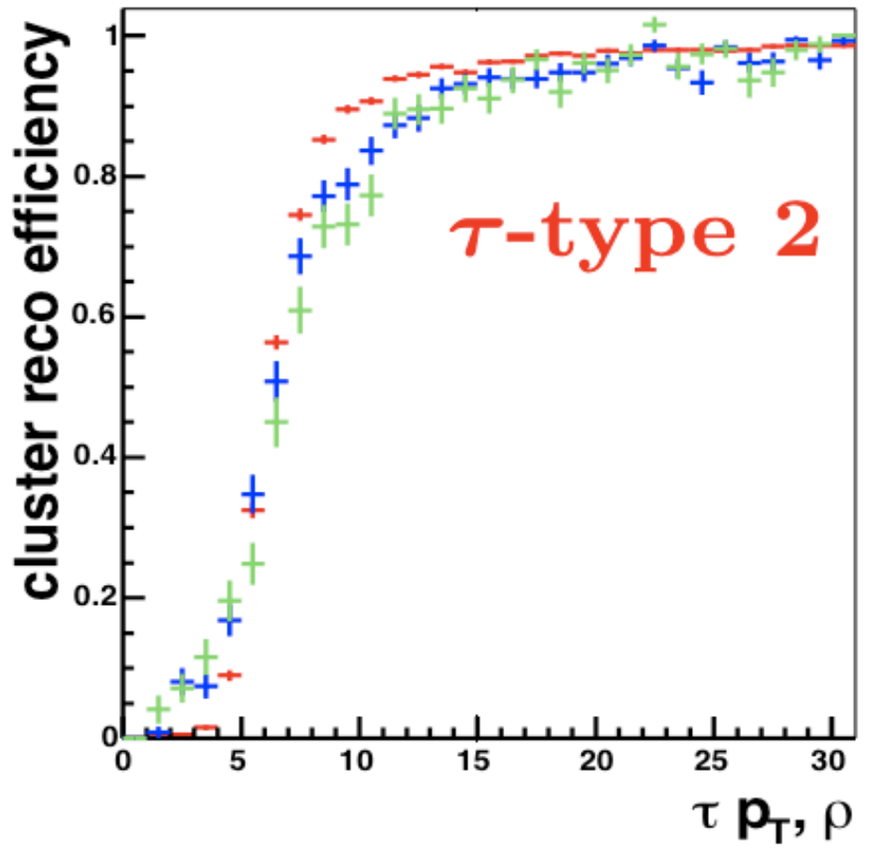
Final state	BR (%)	decay type	notation in this talk	detector properties
e υ υ	17.8 %	leptonic	τ_e	EM id
μ υ υ	17.4 %	leptonic	τ_μ	muon id
π/K υ	11.6 %	1-prong	τ_h	1 track + calo
π/K υ + ≥ 1π^0	37.1 %	1-prong	τ_h	1 track + calo
πππ υ + ≥ 0 π^0	15.2 %	3-prong	τ_h	3 tracks + calo

τ identification

τ signal:
distinguish 3 tau types



NB: electrons are τ_h type2



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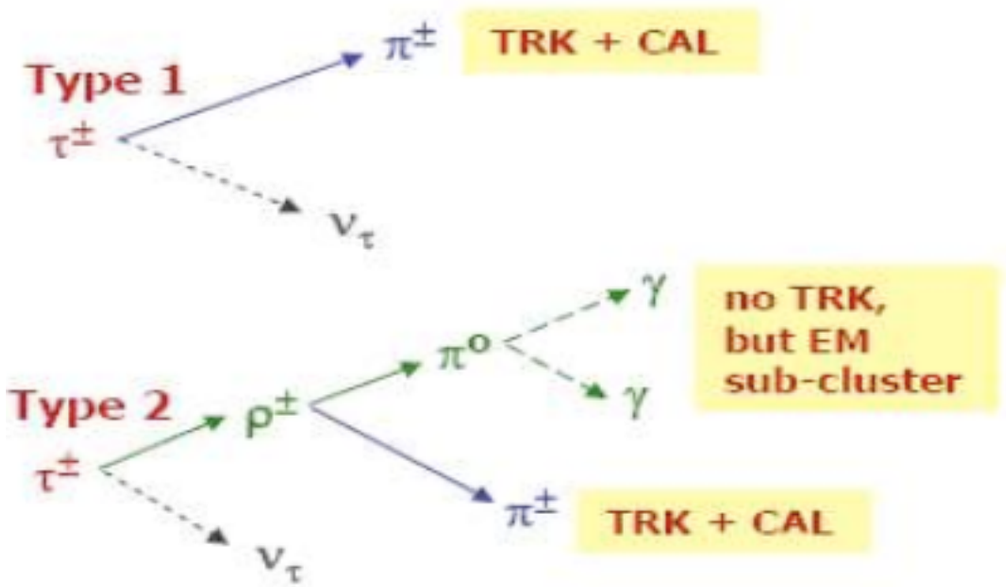
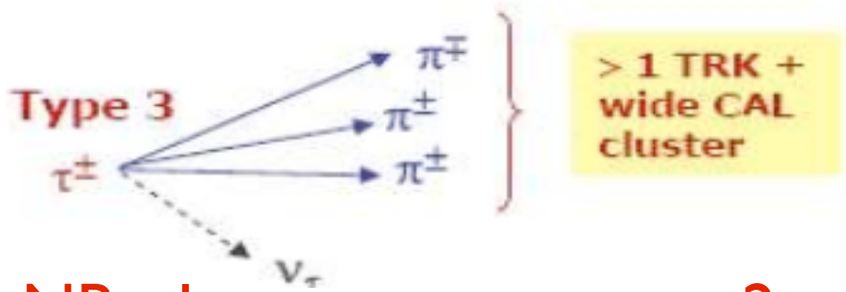
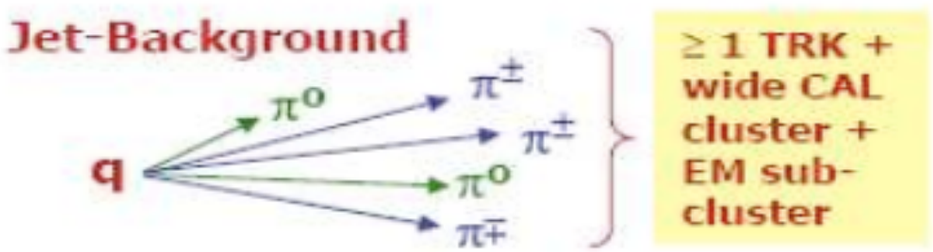
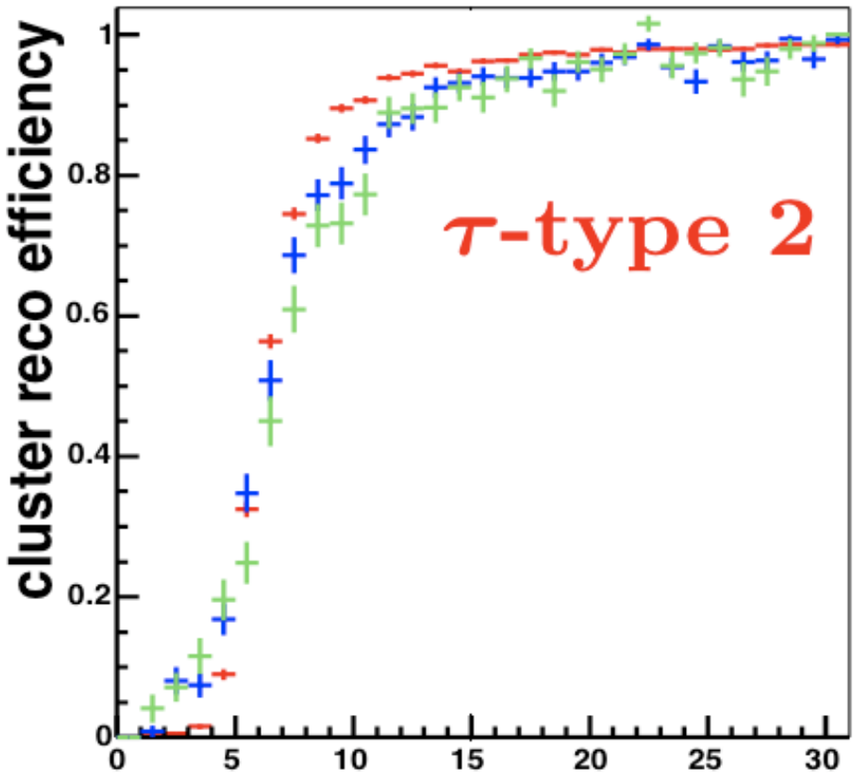




NB: electrons are τ_h type2

jets mimic τs





build a NN based on shower shape and isolation variables.

NN cut effi	τ_h 1	τ_h 2	τ_h 3
jets	3 %	2.5 %	2.5 %
τ	60 %	75 %	65 %

Combine the following channels:

- $\tau_\mu\tau_h$: 2.2 fb^{-1}
- $\tau_e\tau_h$: 1.0 fb^{-1}
- $\tau_\mu\tau_e$: 1.0 fb^{-1}
- $\tau_h\tau_h$: not considered, difficult to trigger on and overwhelmed by multijets background

run2a (1fb^{-1}) result:
Phys. Rev. Lett. **101**, 071804 (2008)

Backgrounds:

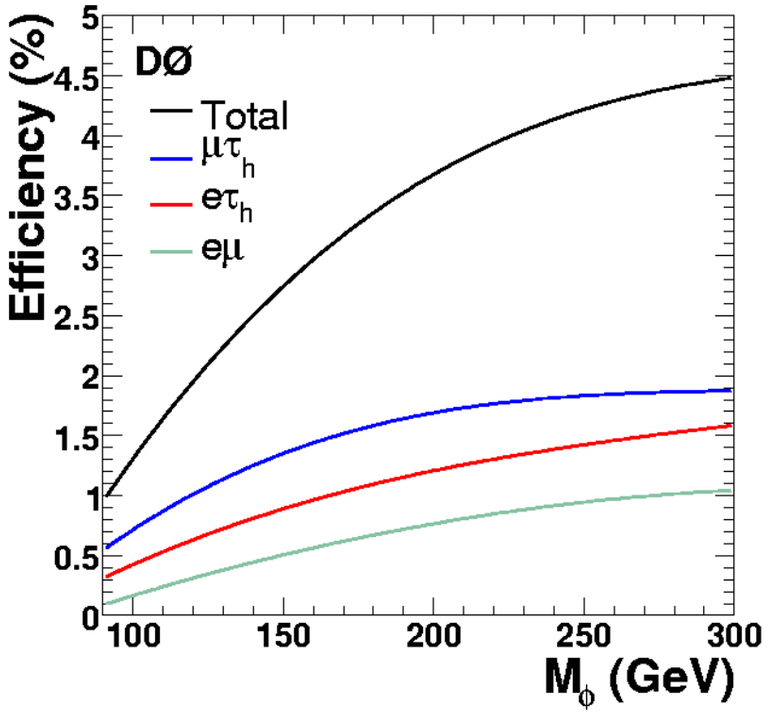
- $Z \to \tau\tau$: MC
- $Z \to \mu\mu/ee$: MC
- $W \to l\upsilon$: MC
- $t\bar{t}$: MC
- dibosons: MC
- multijets: from data

Selections:

1. $\tau_\mu\tau_h$ and $\tau_e\tau_h$:
   opposite charged leptons
   $p_T[h] > 15$ GeV/c & $|\eta_h| < 2$
   NN_τ cuts applied
   $p_T[\mu/e] > 16.5$ GeV/c & $|\eta_\mu| < 2$; $|\eta_e| < 2.5$
   μ/e isolated
   $M_T[W] < 40$ GeV/c^2
   + additional kinematic cuts to remove W
   + additional cuts to remove $Z \to ee$
   + muon veto to kill $Z \to \mu\mu$

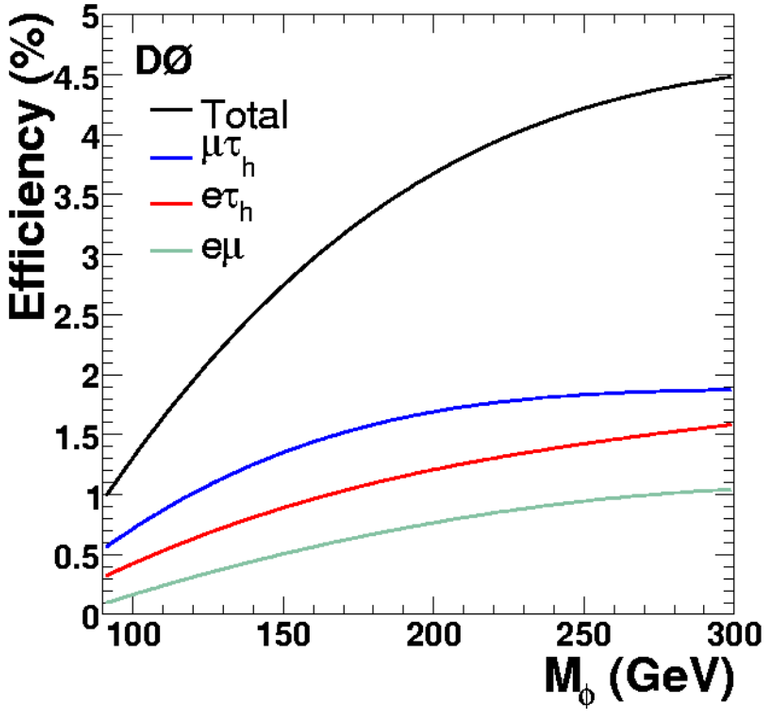
2. $\tau_\mu\tau_e$:
   opposite charged leptons
   $p_T[e] > 12$ GeV/c & $|\eta_\mu| < 1.6$
   $p_T[\mu] > 10$ GeV/c & $|\eta_e| < 2.0$
   μ/e isolated
   $M_T[W]\text{min} < 10$ GeV/c^2
   $p_T[e] + p_T[\mu] + mE_T > 65$ GeV/c
   $\Delta\varphi\text{min}[e/\mu\ ; mE_T] < 0.3$
   $H_T < 70$ GeV/c

Best channel: $\tau_\mu \tau_h$



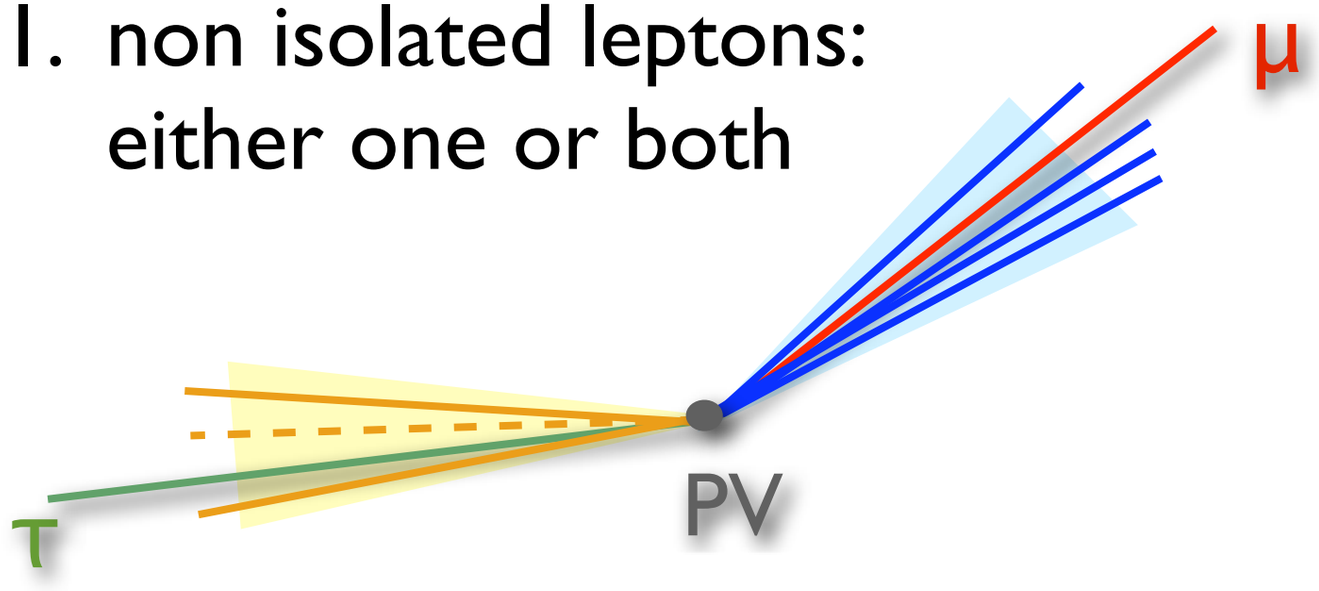
- Multijets estimated from 2 samples:

Best channel: $\tau_\mu \tau_h$



- Multijets estimated from 2 samples:

1. non isolated leptons: either one or both



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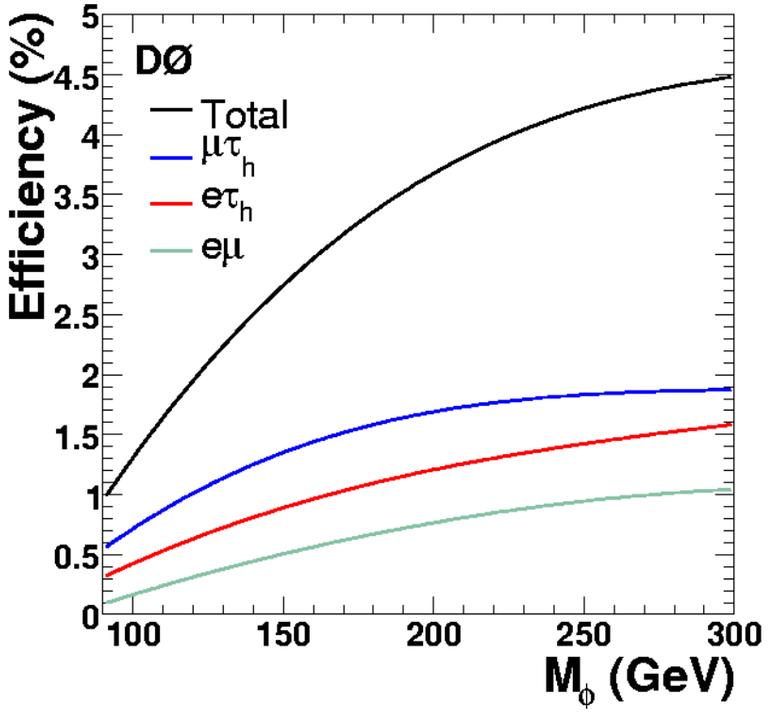

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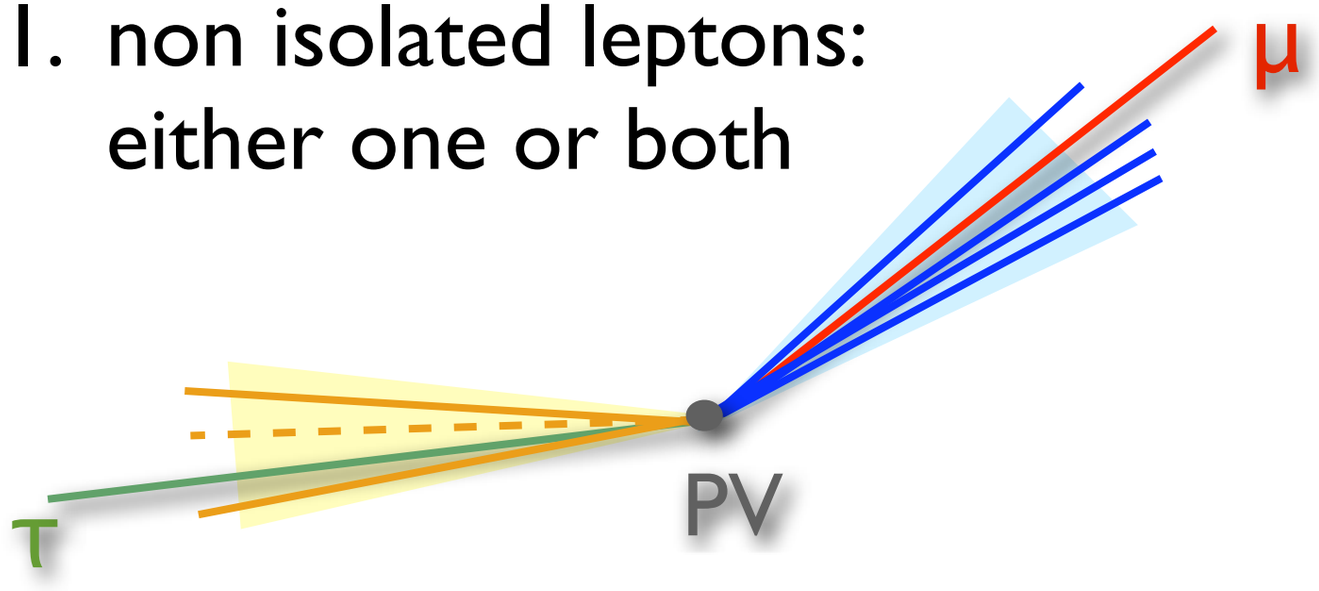
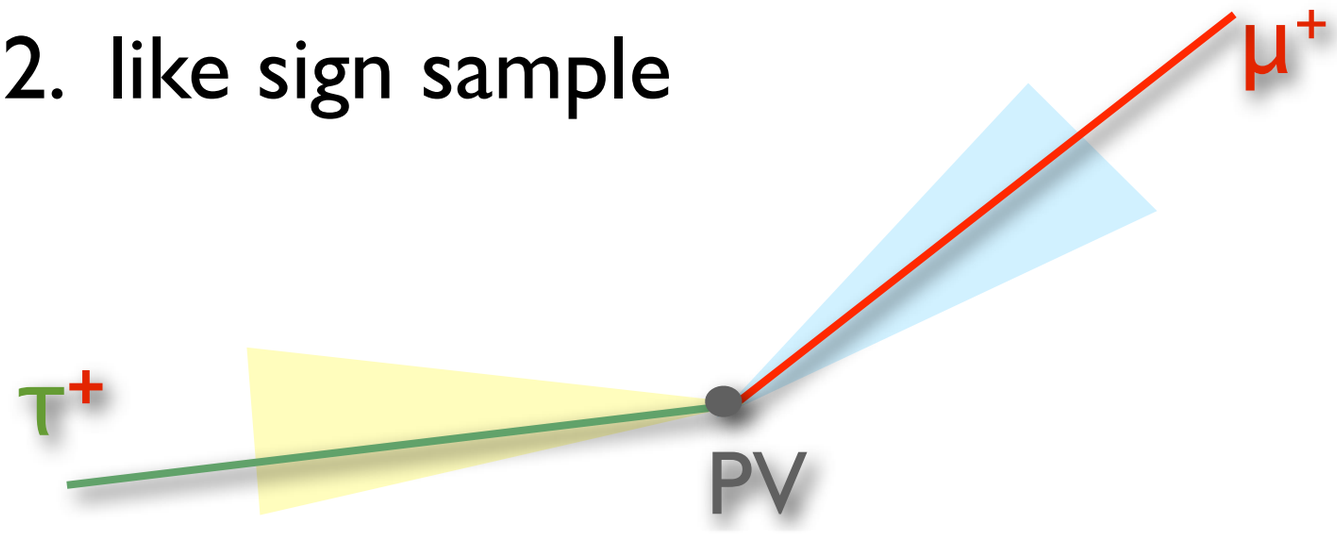
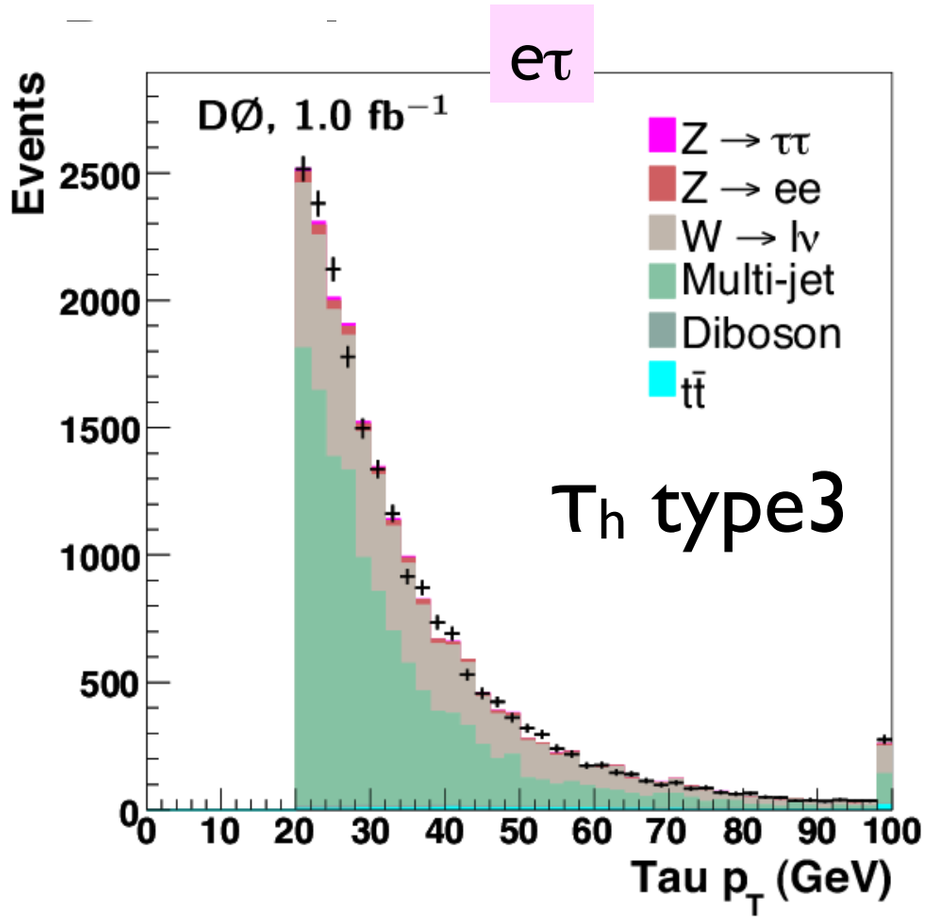


2. like sign sample



inclusive $h \to \tau\ \tau$



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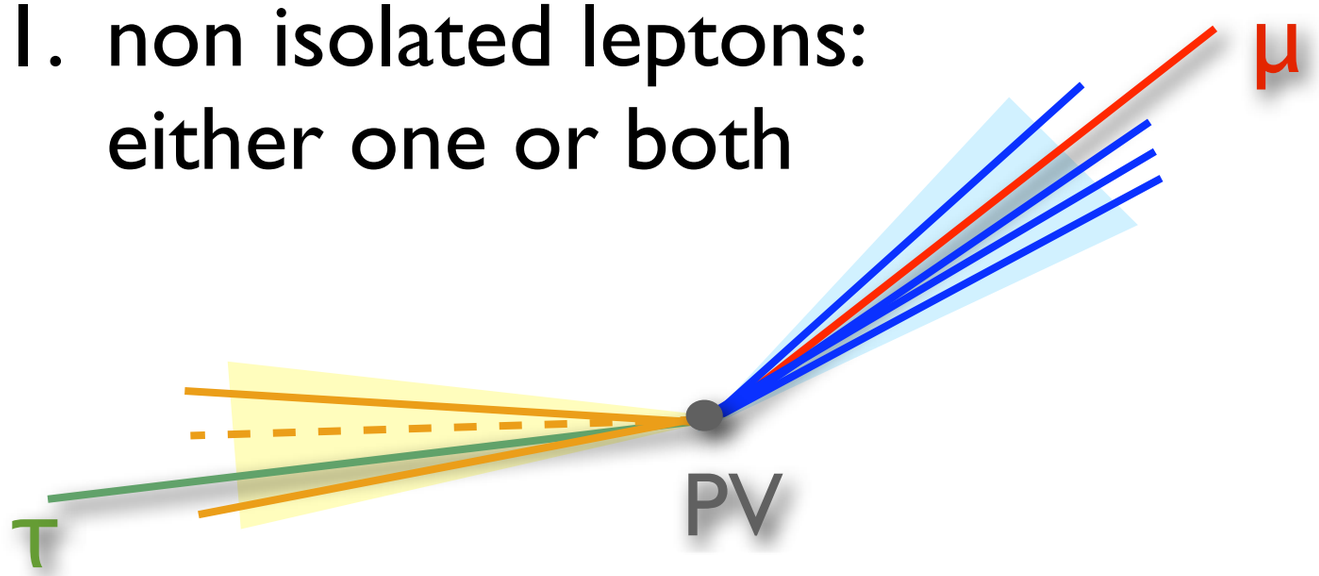
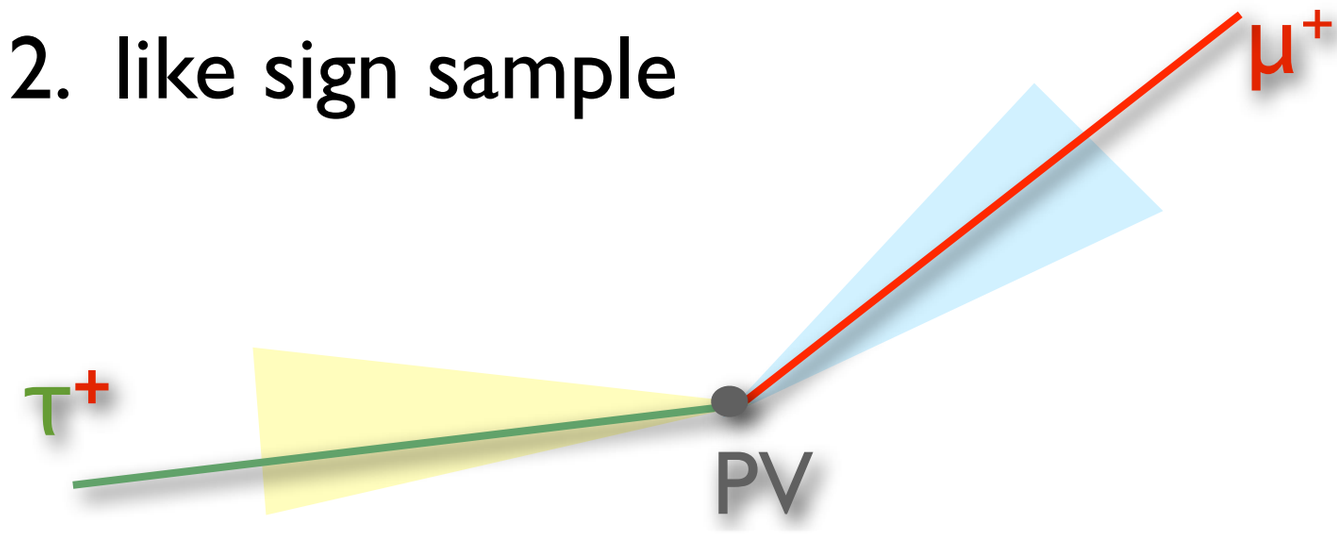


- In W MC, τ_h fake is also corrected for

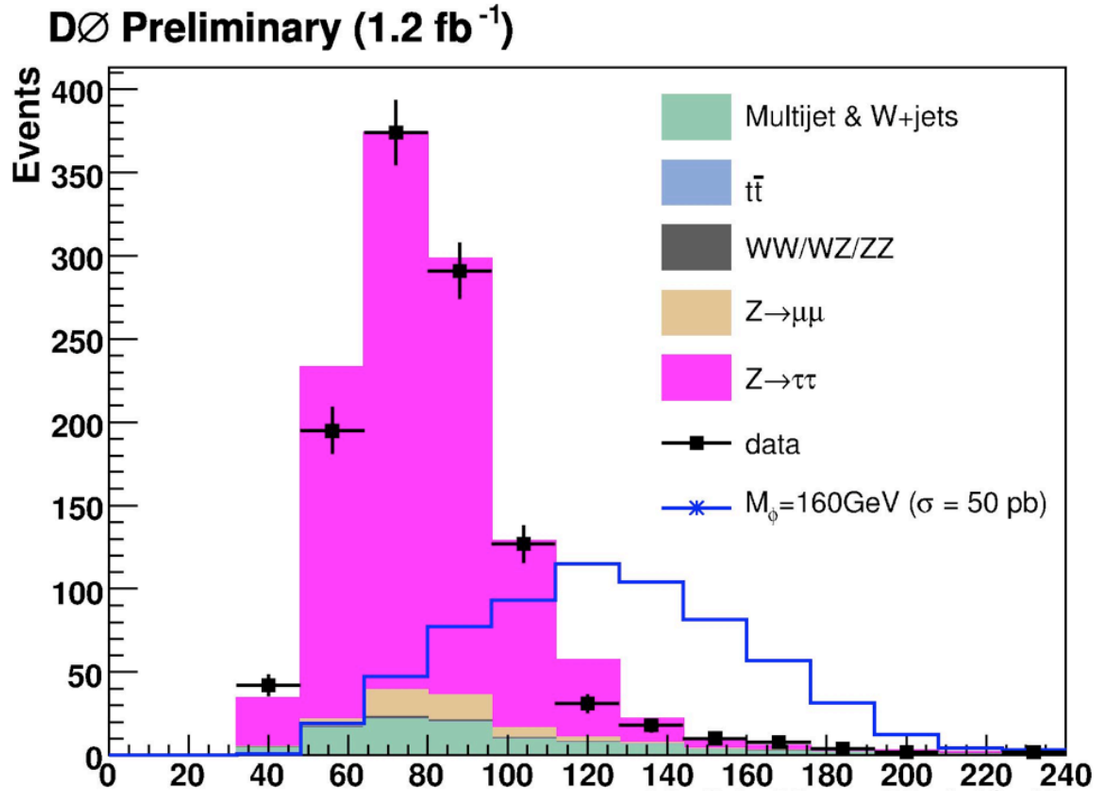
2. like sign sample



Discriminating variable

neutrino escape detection, but one can still use $\not\!\!E_T$:

$$M_{vis} = \sqrt{p_{\tau_h} + p_\mu + \not\!\!E_T}$$



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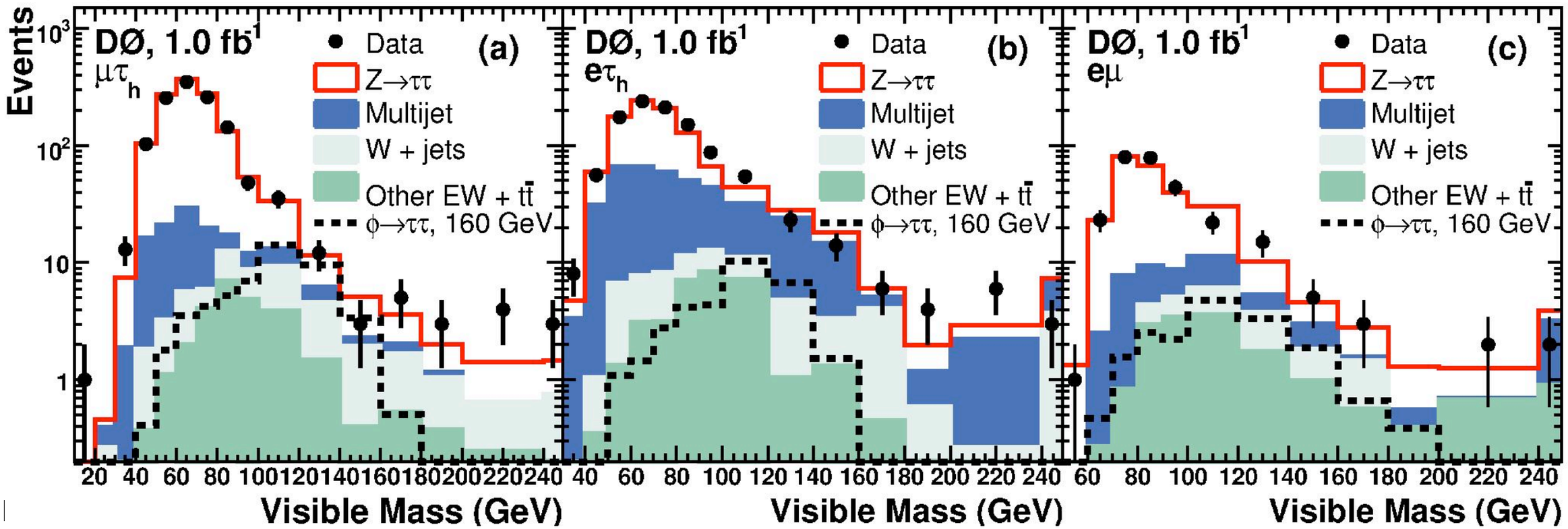
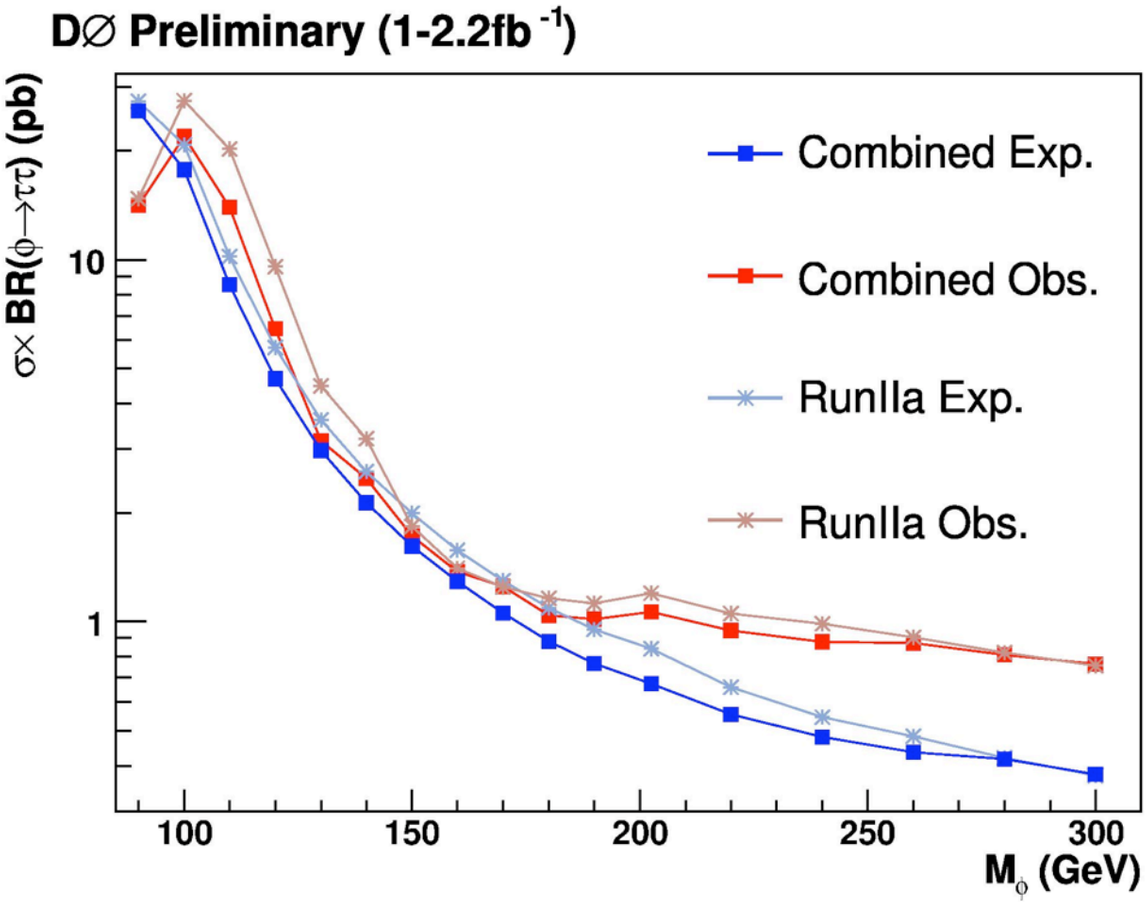
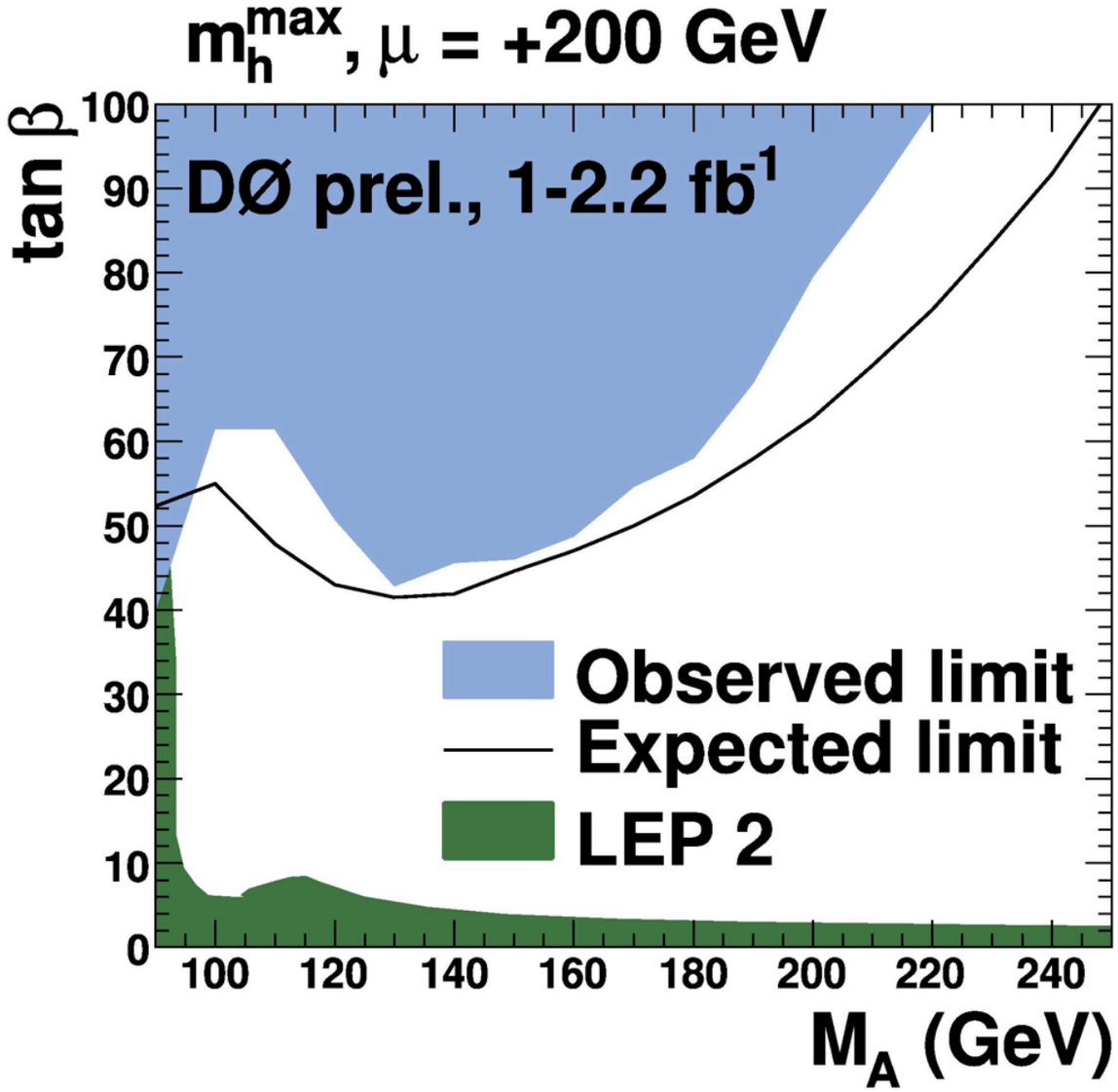


- Data are compatible with background
- Set limits: Φ width effect negligible



model independent limit

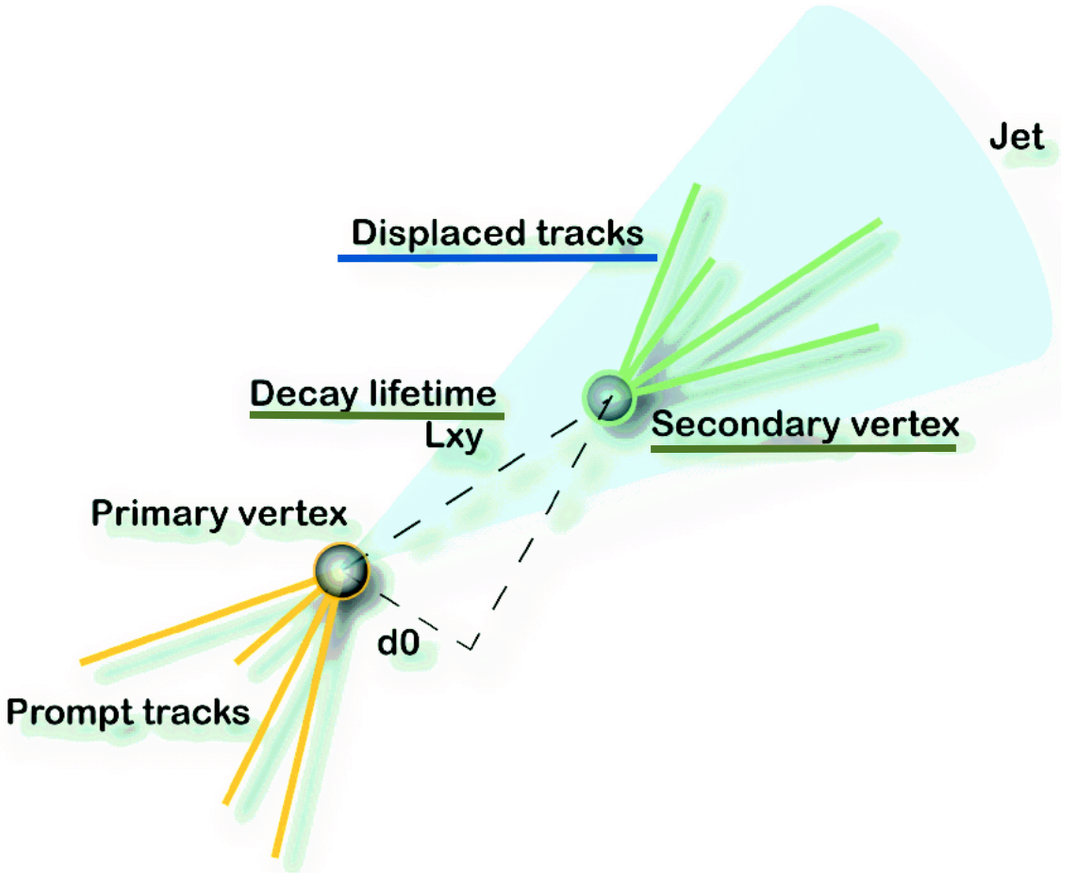


- $b\Phi \rightarrow bbb$ selection:
  - 3 to 5 high p_T jets: $p_T > 20$ GeV/c $|\eta| < 2.5$
  - at least 3 b-tagged jets
  - 2 leading b-tagged jets with $p_T > 25$ GeV/c

- Main challenges:
  - Large multijets background: trigger on multijets events + impact parameter b-tag (60-70% efficient)
  - Need a powerful b-tagger to reject the abundant multijet background
  - Modelling of the multijets background

b-jet identification

bΦ→bbb: must discriminate b-jets vs light jets



Tagging b jets:

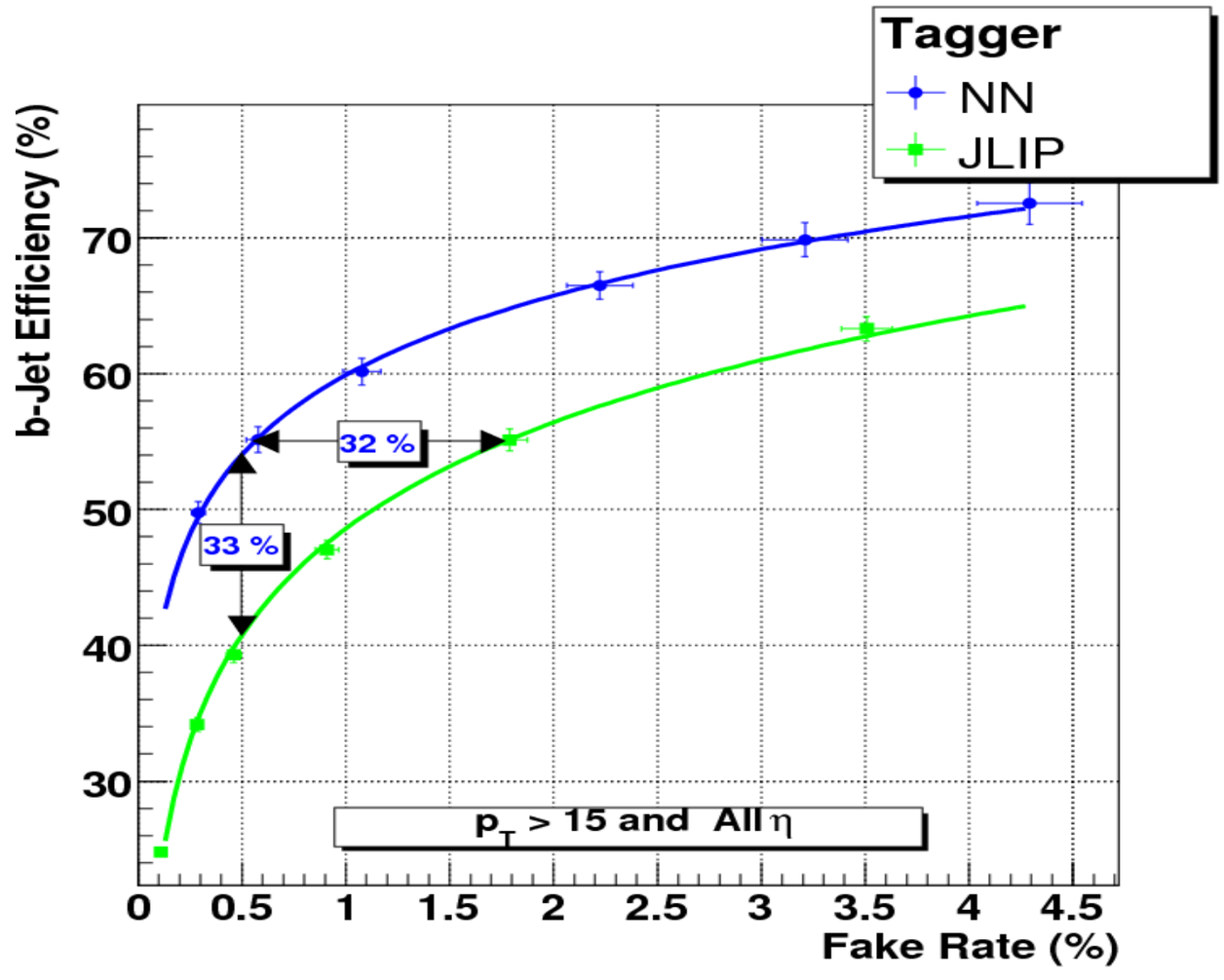
b hadrons: long life time + heavy

- secondary vertices, decay life time
- displaced tracks
- vertex mass

b-tagging examples @ DØ

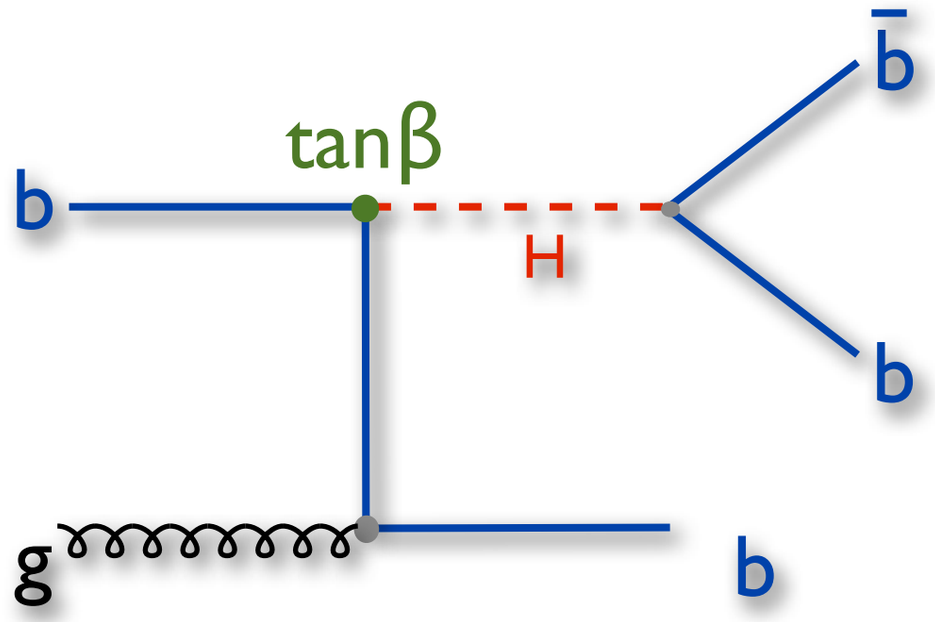
infos combined in a Neural Network

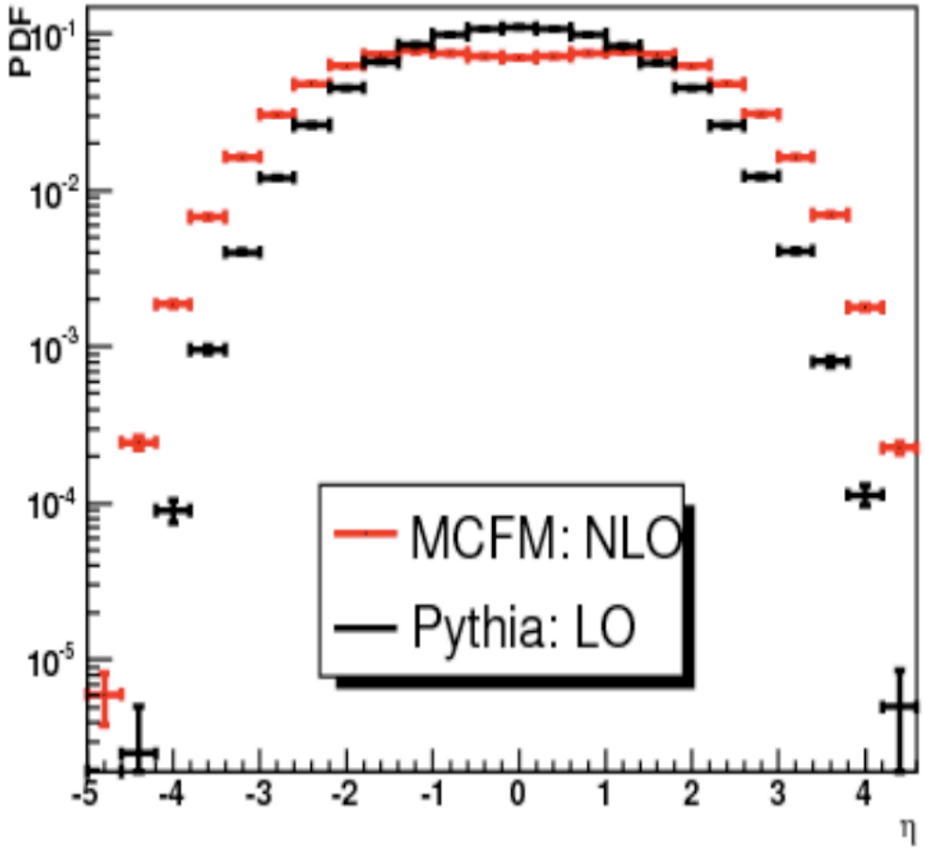
- efficiency (b quarks): 50% / 70%
- fake rate (light jets): 0.5% / 4.5%

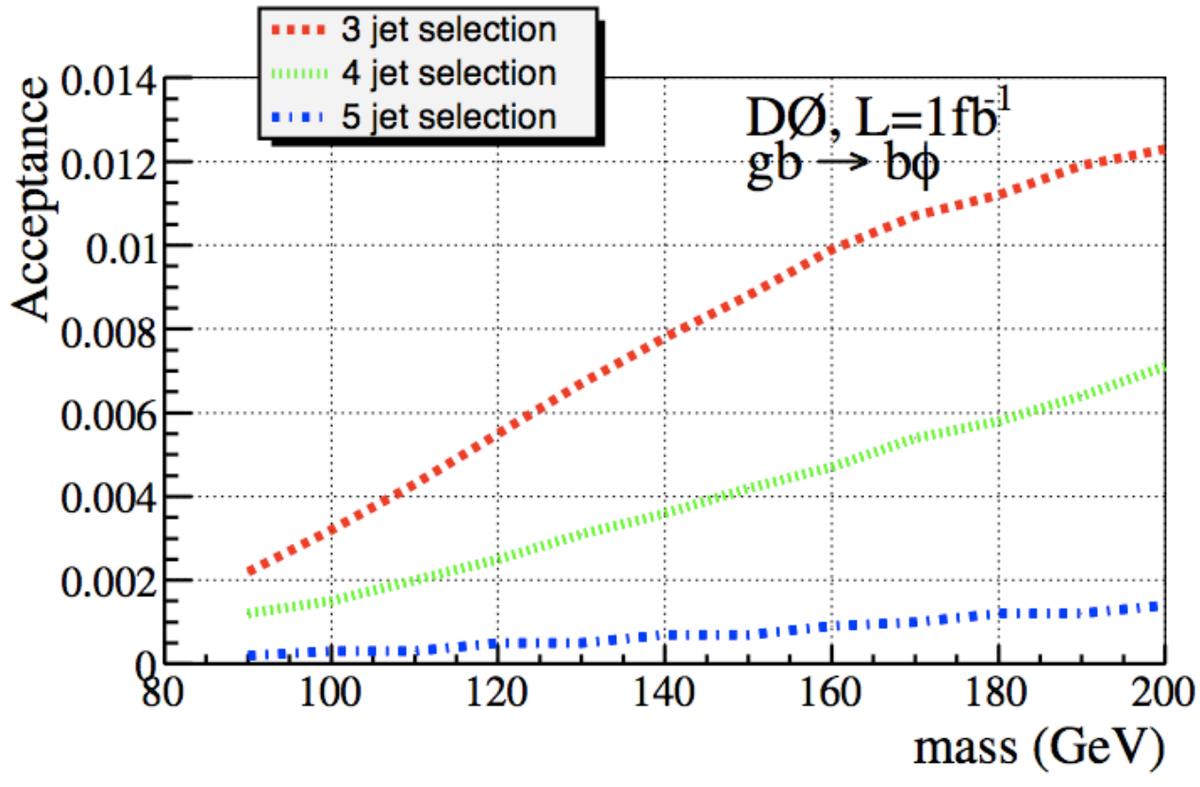


Signal simulation

- Pythia bg → bH
- spectator b quark kinematics reweighted to NLO (MCFM)



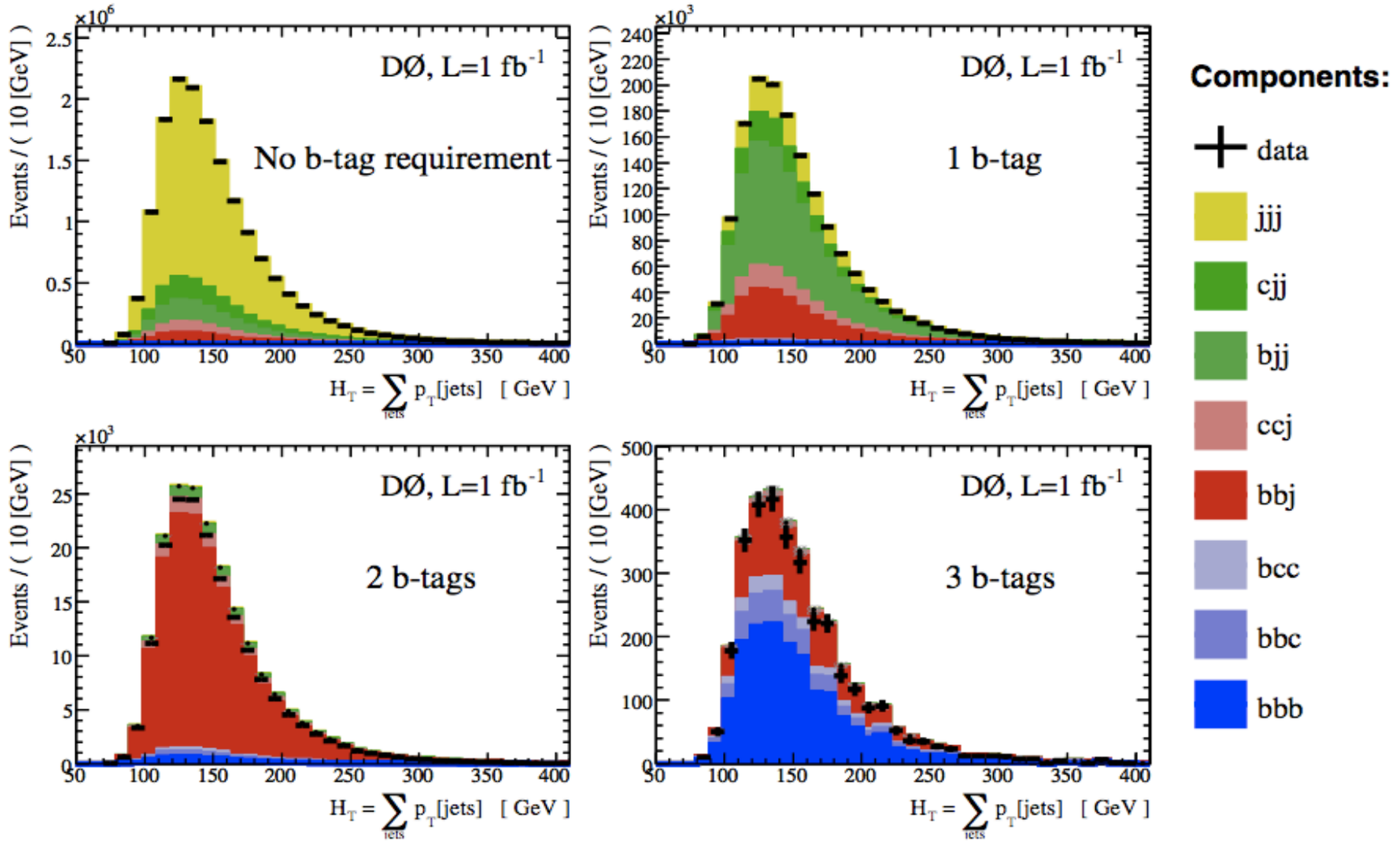




Background modelling

- bbb (irreducible), bbc, bcc, bbj, ccj... where j is a light parton.
- Relative fractions are measured in data using several b-tagging operating points.
- NB: the total background normalisation is not known, taken into account by the limit setting procedure.

Example of the 3-jets channel



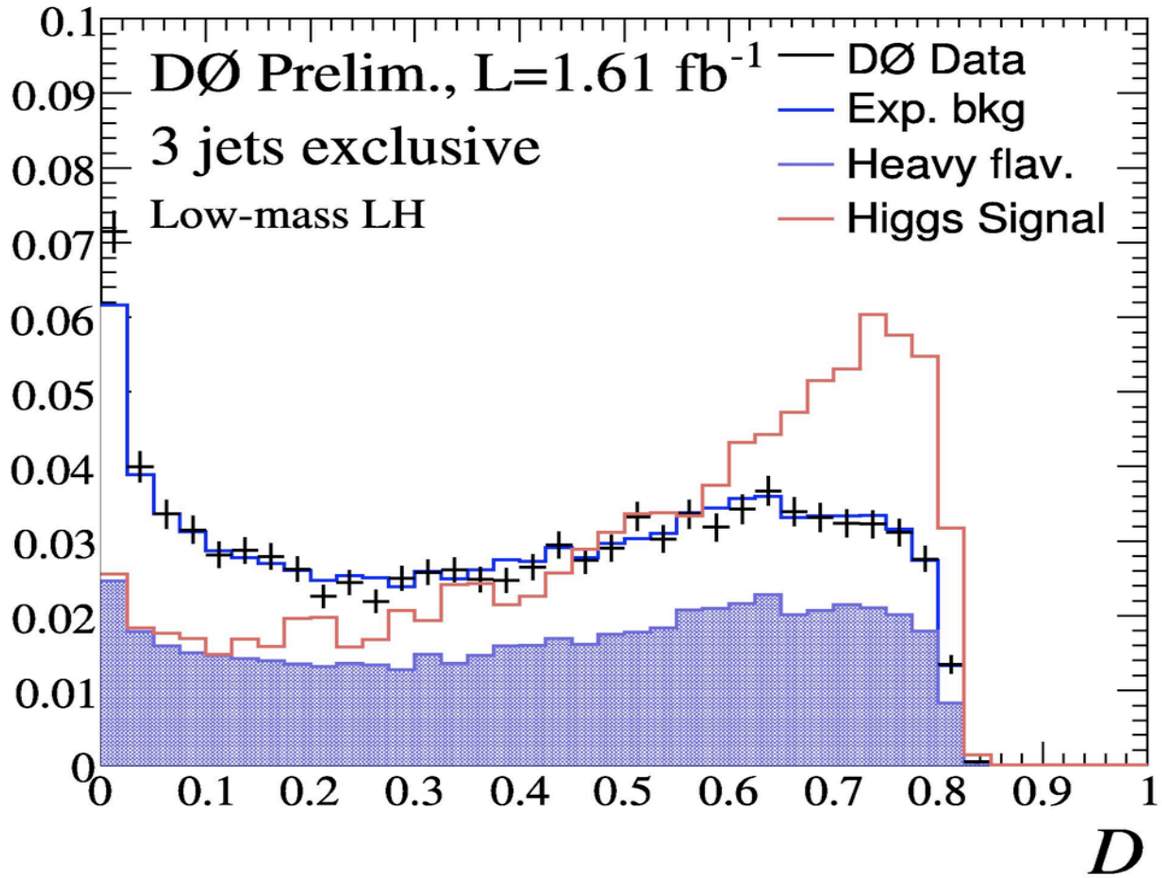
Background modelling

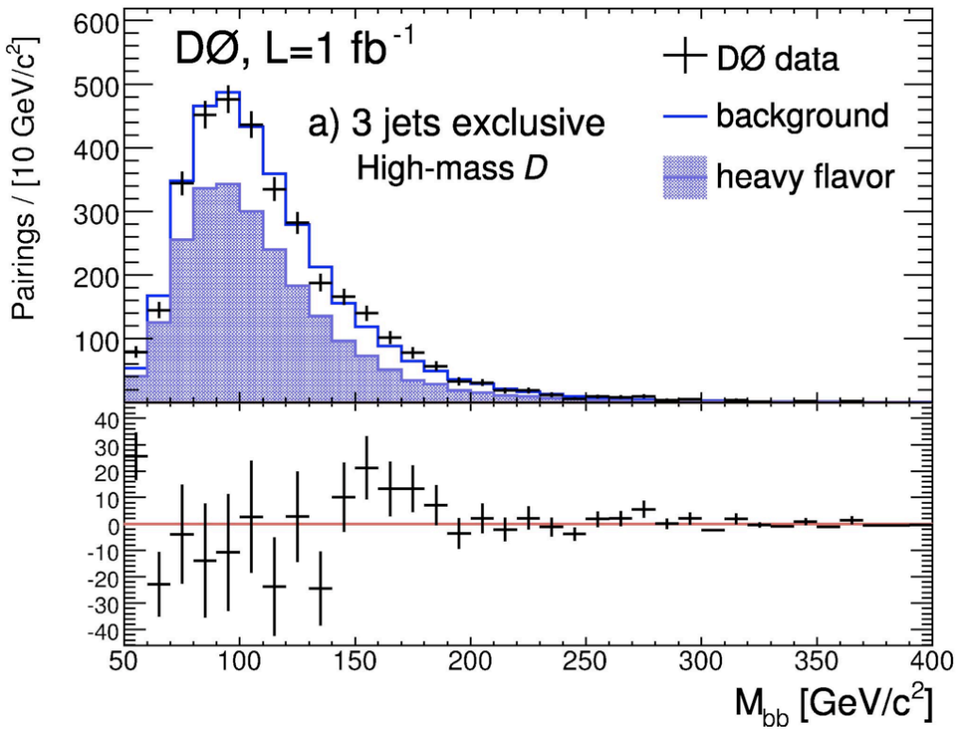
- MC simulation (ALPGEN+PYTHIA) of bbj and bbb, bbc, bcc backgrounds.
- Variable shapes from 2 b-tagged sample (dominated by bbj, signal contribution negligible) in data and corrected with the MC:

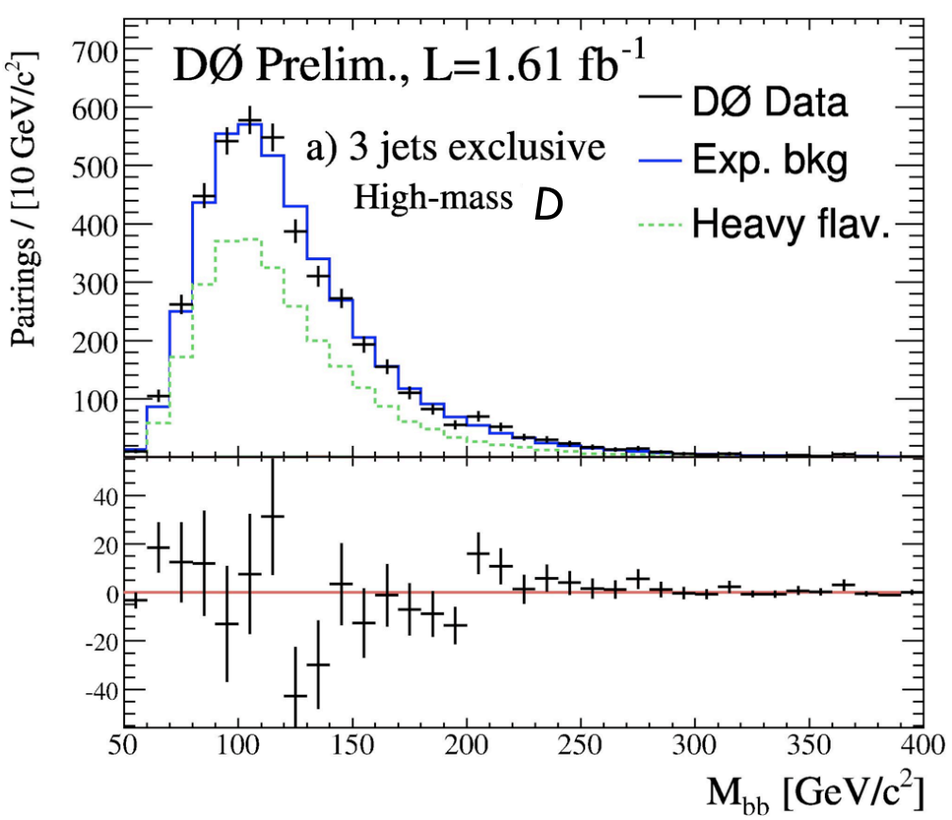
$$S^{exp}_{3tag}(M_{bb},\mathcal{D}) = \frac{S^{MC}_{3tag}(M_{bb},\mathcal{D})}{S^{MC}_{2tag}(M_{bb},\mathcal{D})} \times S^{DATA}_{2tag}(M_{bb},\mathcal{D})$$

- Signal enhancement:

  D is a kinematic likelihood trained to enhance signal vs background discrimination
  ⇒ cut on D







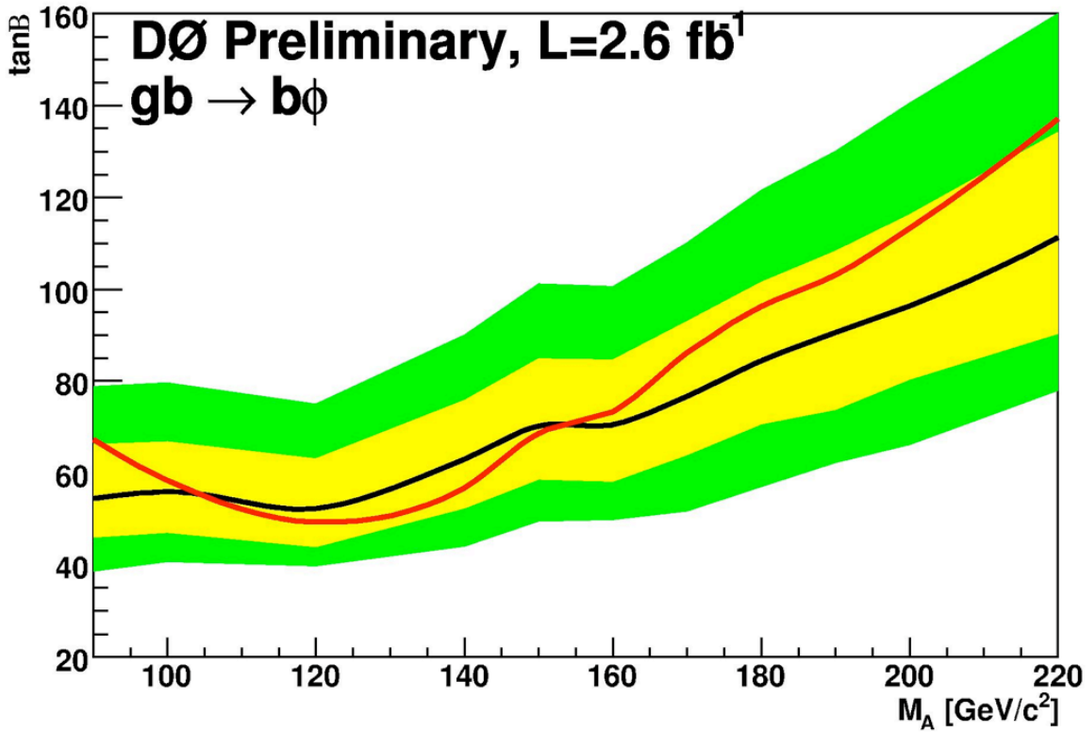
Data samples:

- run 2a: 1 fb^{-1} PRL101, 221802 (2008)
- run 2b: 1.6 fb^{-1}

- Data compatible with background
- Place limits:

  first in the narrow width approximation, ie

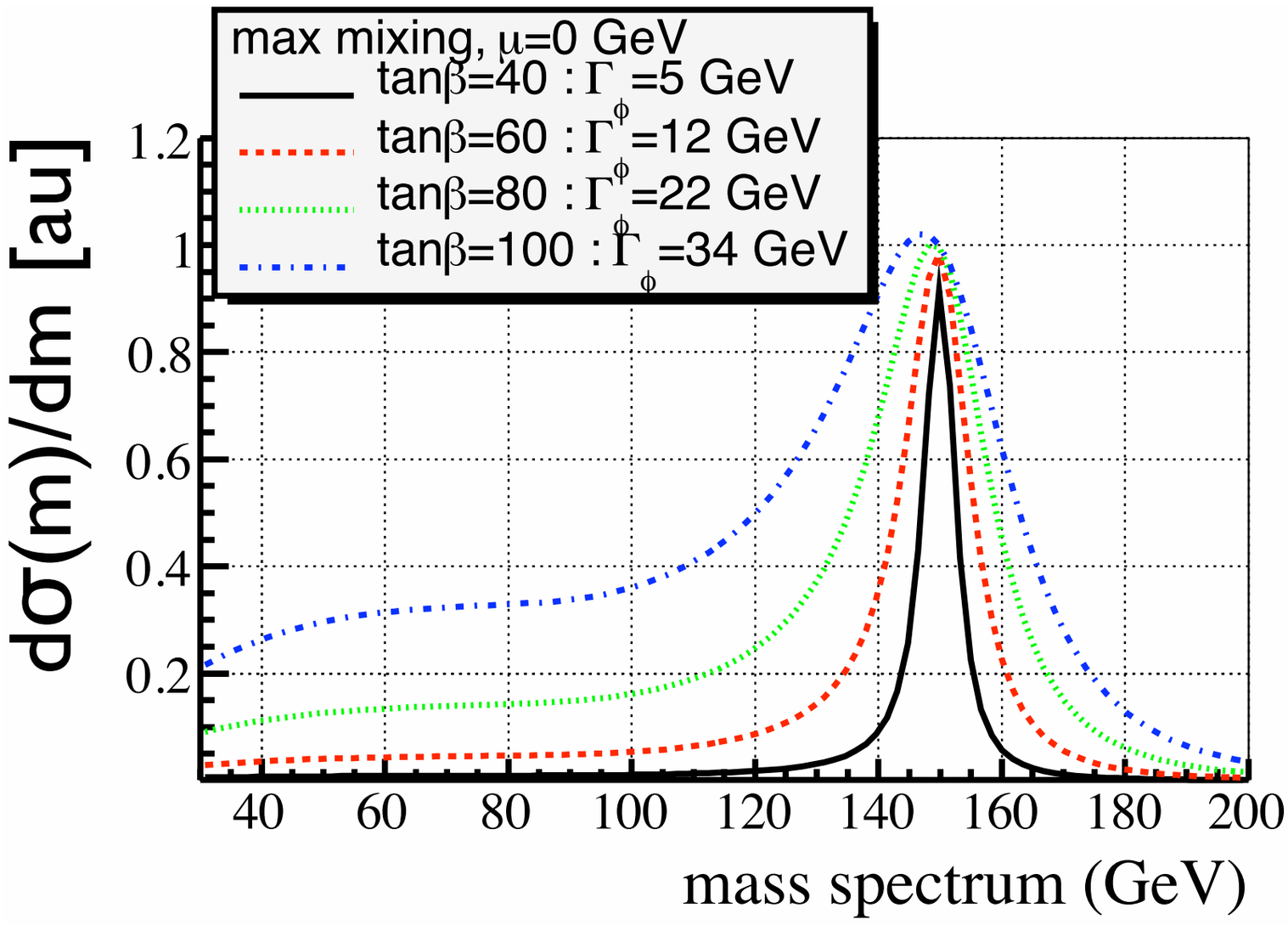
$$\frac{\sigma_{MSSM}}{\sigma_{SM}} = 2 \times tan^2\beta$$



MSSM interpretation

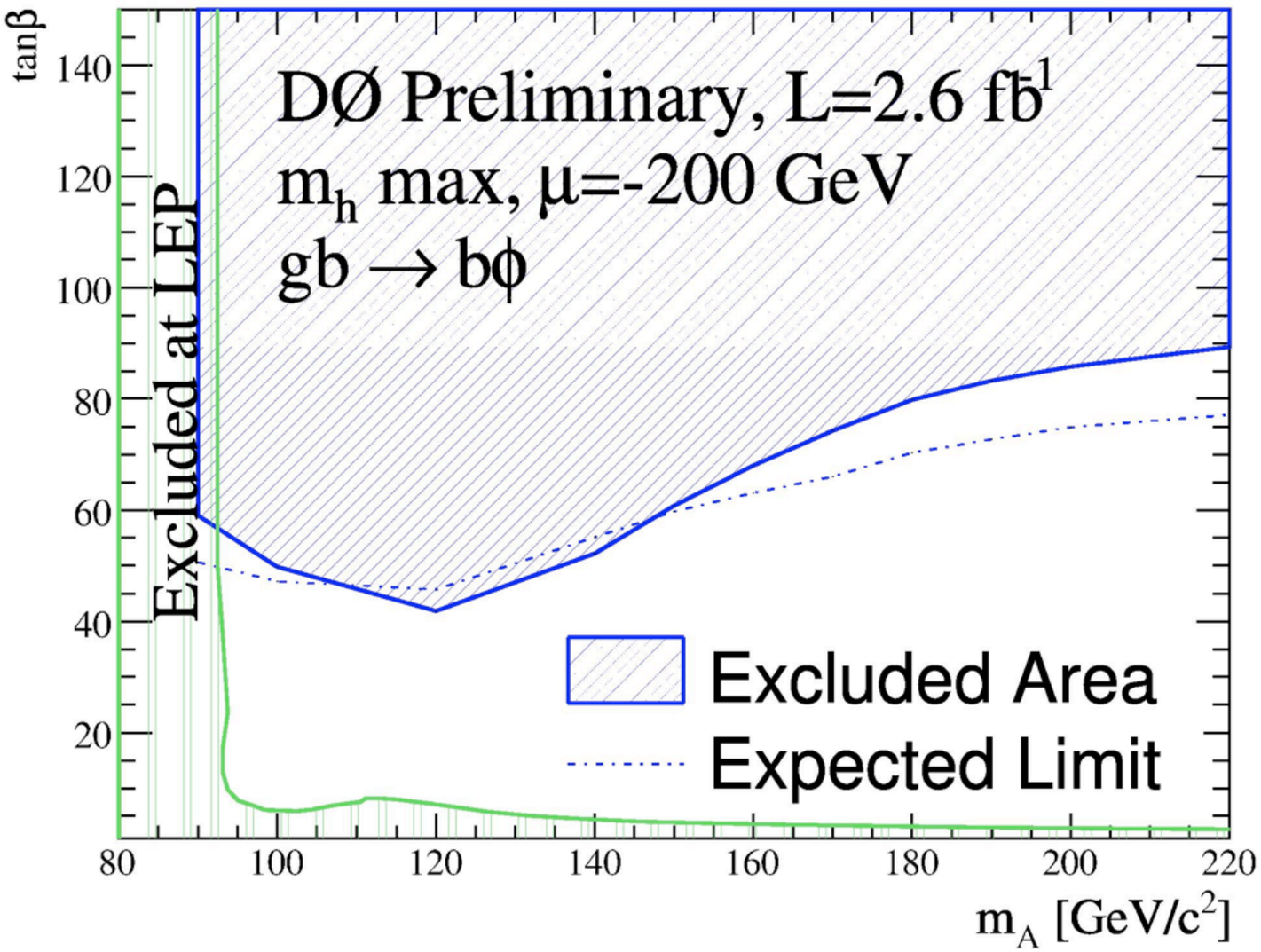
For high tanβ, the Higgs boson width is not negligible compared to the experimental mass resolution.

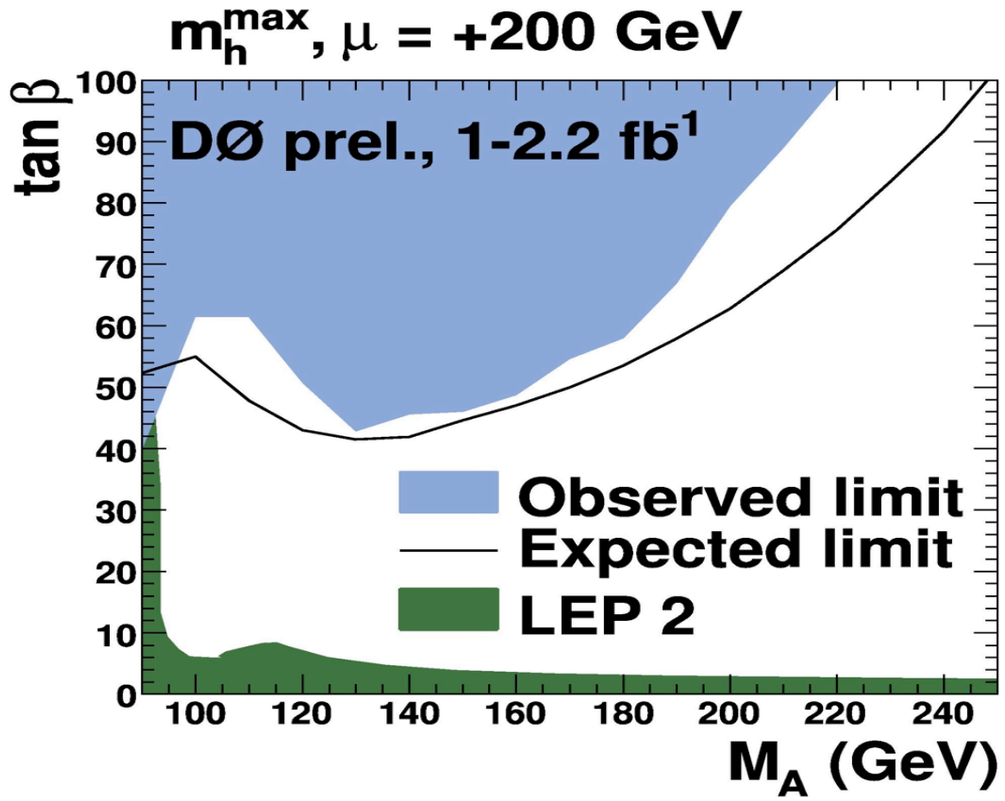
$$\frac{d\sigma}{dm} = \sigma(m, \tan\beta, \Gamma = 0) \times BW(m, m_\phi, \tan\beta)$$



Simulated by a weighted combination of the different Higgs-mass MC samples.

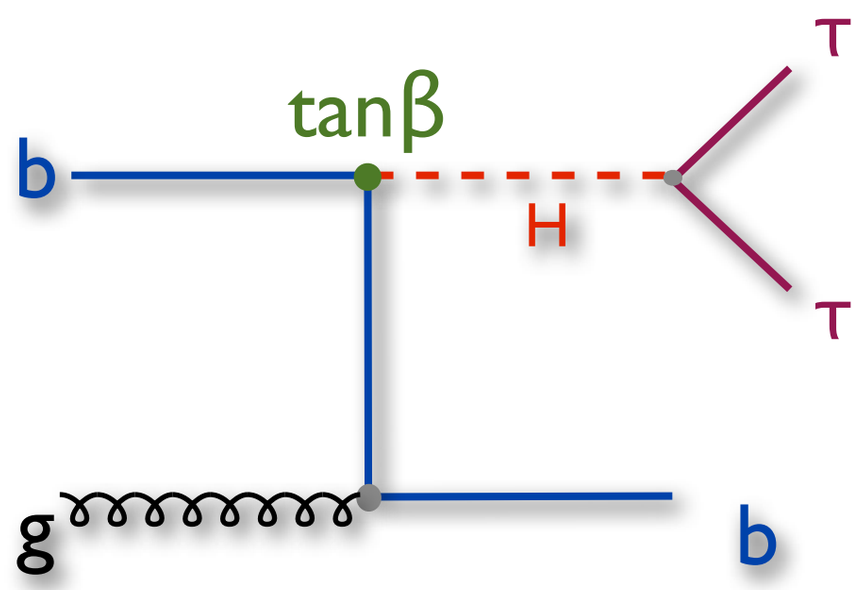
MSSM interpretation





$b\Phi \rightarrow b\tau\ \tau$

- Channel complementary to
  - $b\Phi \rightarrow bbb$: lower Br but much lower background, less sensitive to radiative correction
  - $\Phi \rightarrow \tau\tau$: more sensitive near the Z peak
- Only $b\tau_\mu\tau_h$: 2.7 fb^{-1}
- Triggers: μ & $\mu+\tau$ triggers (for the last 1.7 fb^{-1} of data)!



Backgrounds:

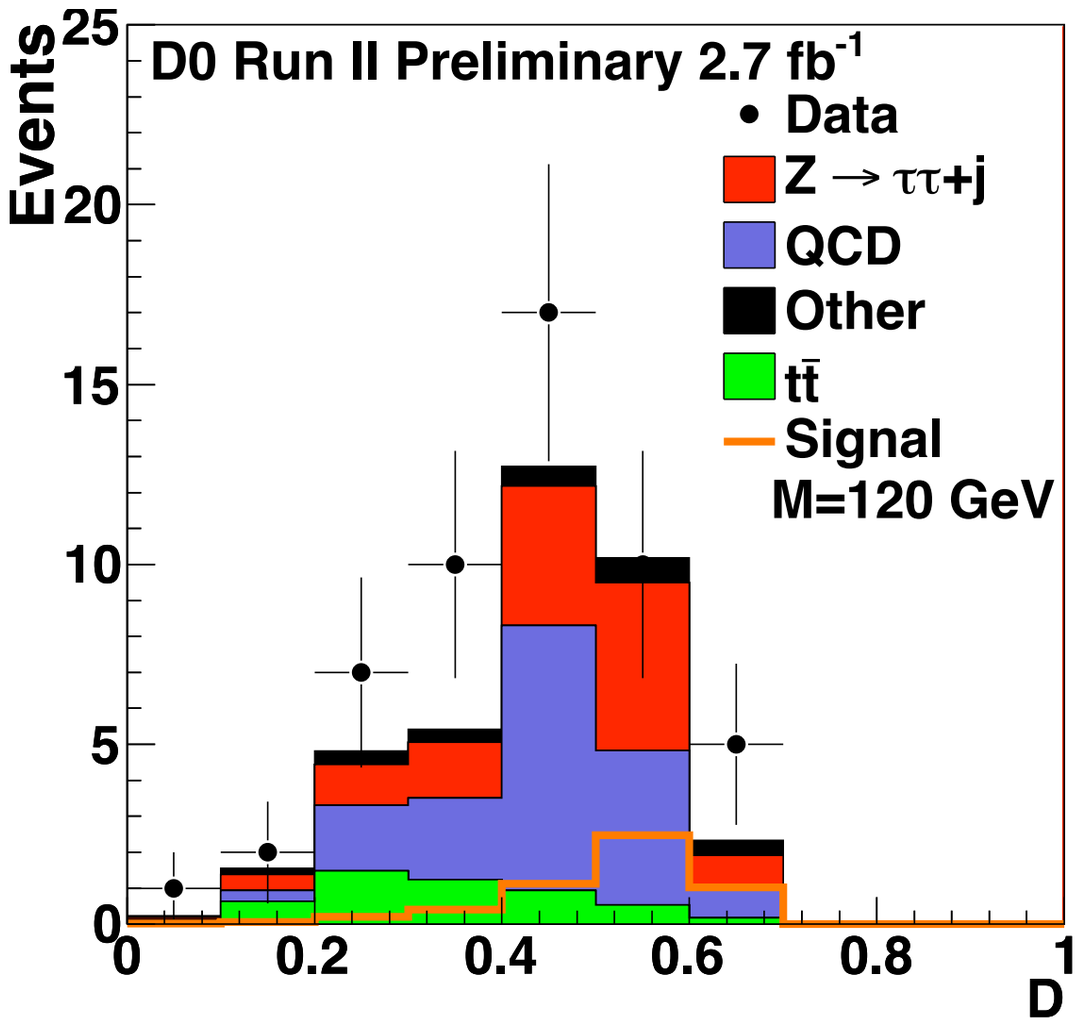
- $Z \rightarrow \tau\tau$: MC
- $t\bar{t}$: MC
- Multijets: from data

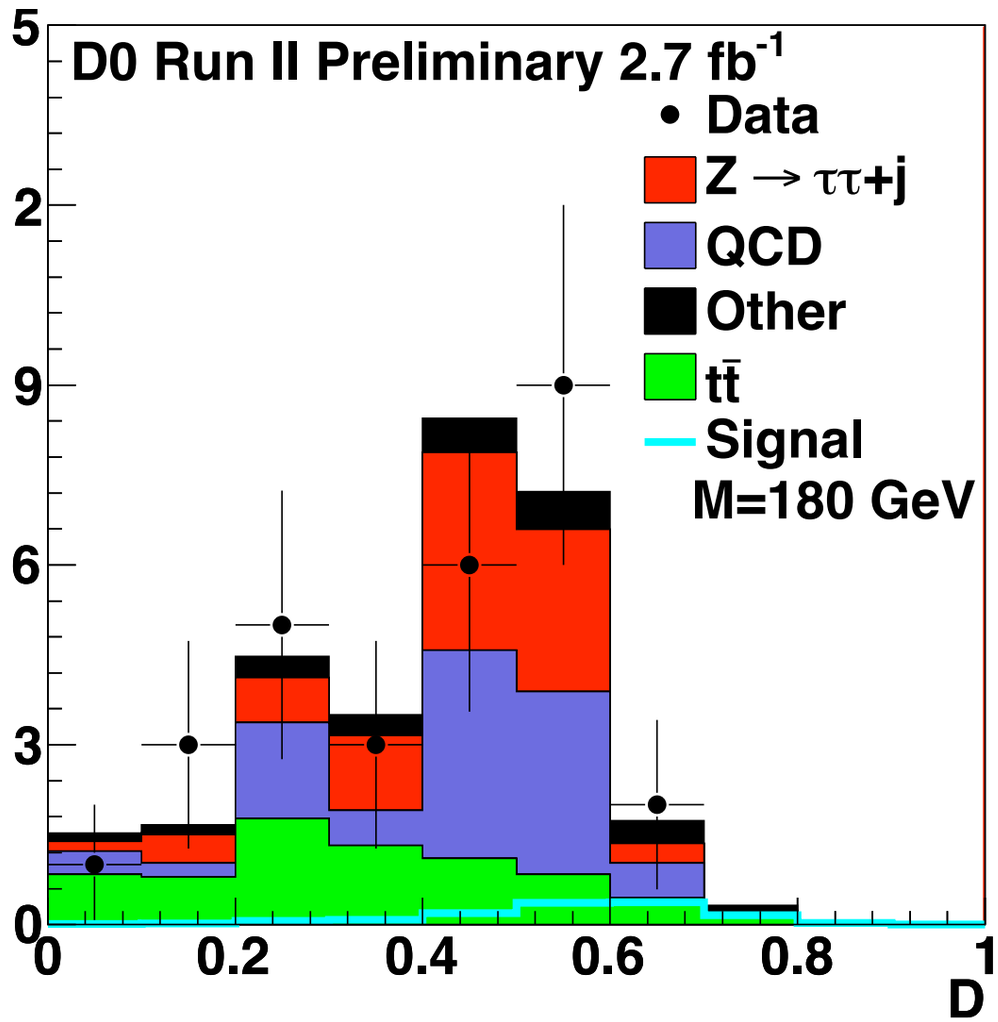
Selection:

opposite charged leptons
$p_T[h] > 10$ GeV/c (15 for type 3)
NN_τ cuts applied
$p_T[\mu] > 12$ GeV/c & $|\eta_\mu| < 2$ & iso μ
$M_T[W] < 80$ GeV/c^2 (60 for type 3)
at least 1 jet with pT>15GeV/c & $|\eta_{jet}| < 2.5$
at least 1 b-tagged jet.

Discriminating variable

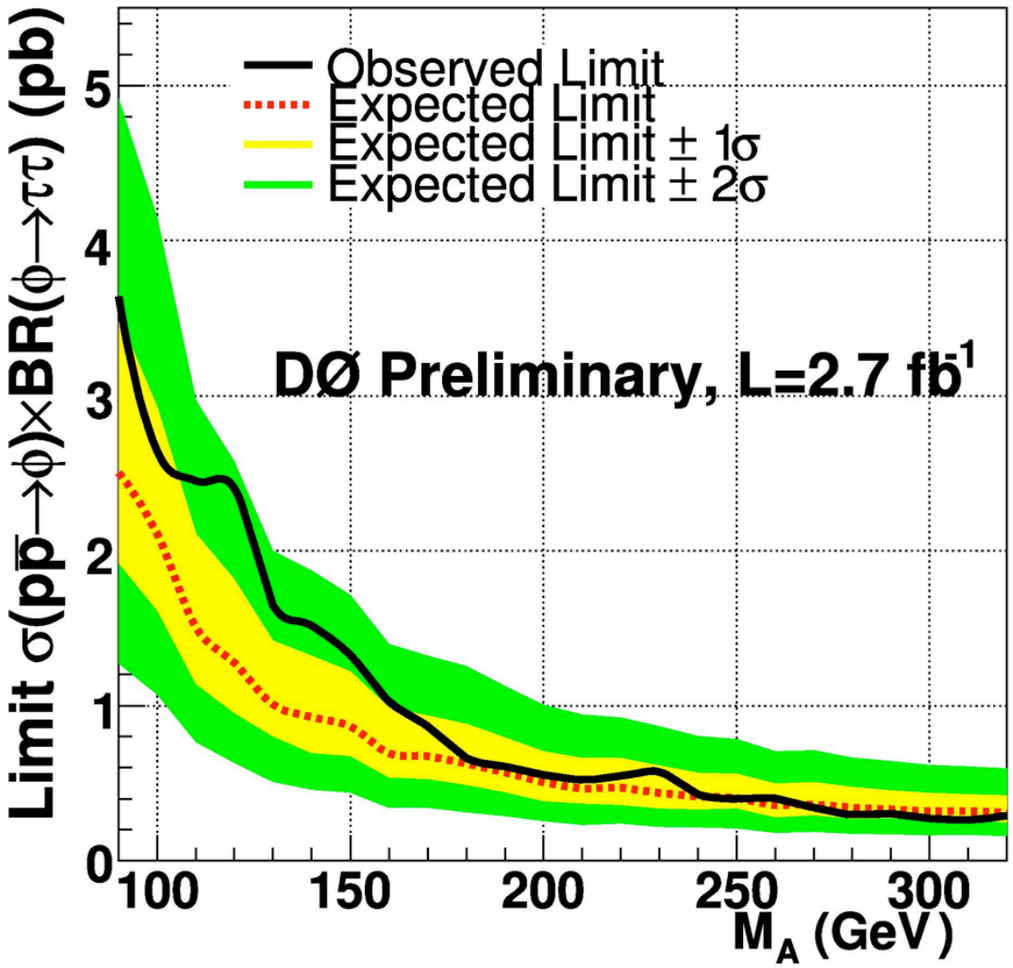
- Main backgrounds are $t\bar{t}$ and multijets.
  - NN against $t\bar{t}$
  - LH against multijets
  - cut on both on NN and LH
  - use D = NN x LH as discriminating variable

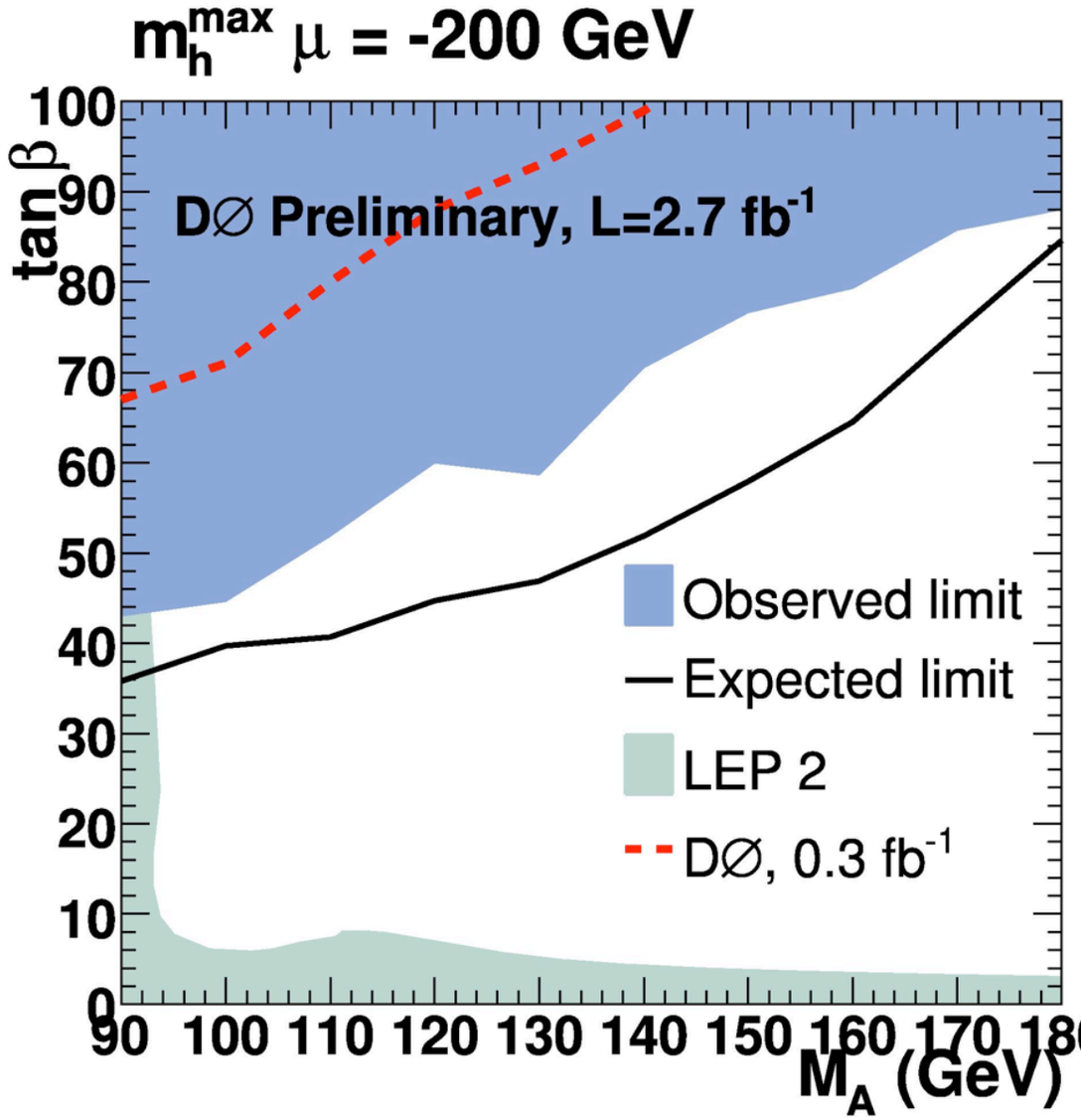




- Data compatible with background
- In the MSSM interpretation, the Φ width taken into account as in bbb analysis

model independent limit





as sensitive as bbb at low mass!

Neutral Higgs searches combinations

DØ combo: principle & inputs

Channel	Integrated Luminosity / fb^{-1} Run IIa	Run IIb	Final Variable
$h \to \tau_e \tau_{\mathrm{had}}$	1.0	-	visible mass
$h \to \tau_\mu \tau_{\mathrm{had}}$	1.0	1.2	visible mass
$h \to \tau_e \tau_\mu$	1.0	-	visible mass
$bh \to b\tau_\mu \tau_{\mathrm{had}}$	-	1.2	1D-discriminant
$bh \to bb\bar{b}$	1.0	1.6	M_{bb}

- The different channels are complementary:
  - Different sources of systematics
  - Different influences of radiative corrections
  - Model-independent combination is not meaningful
- Combine 19 sub-channels in total
- Combination is done using the modified frequentist method known as CL_s using in addition a profile likelihood technique to reduce the impact of systematics

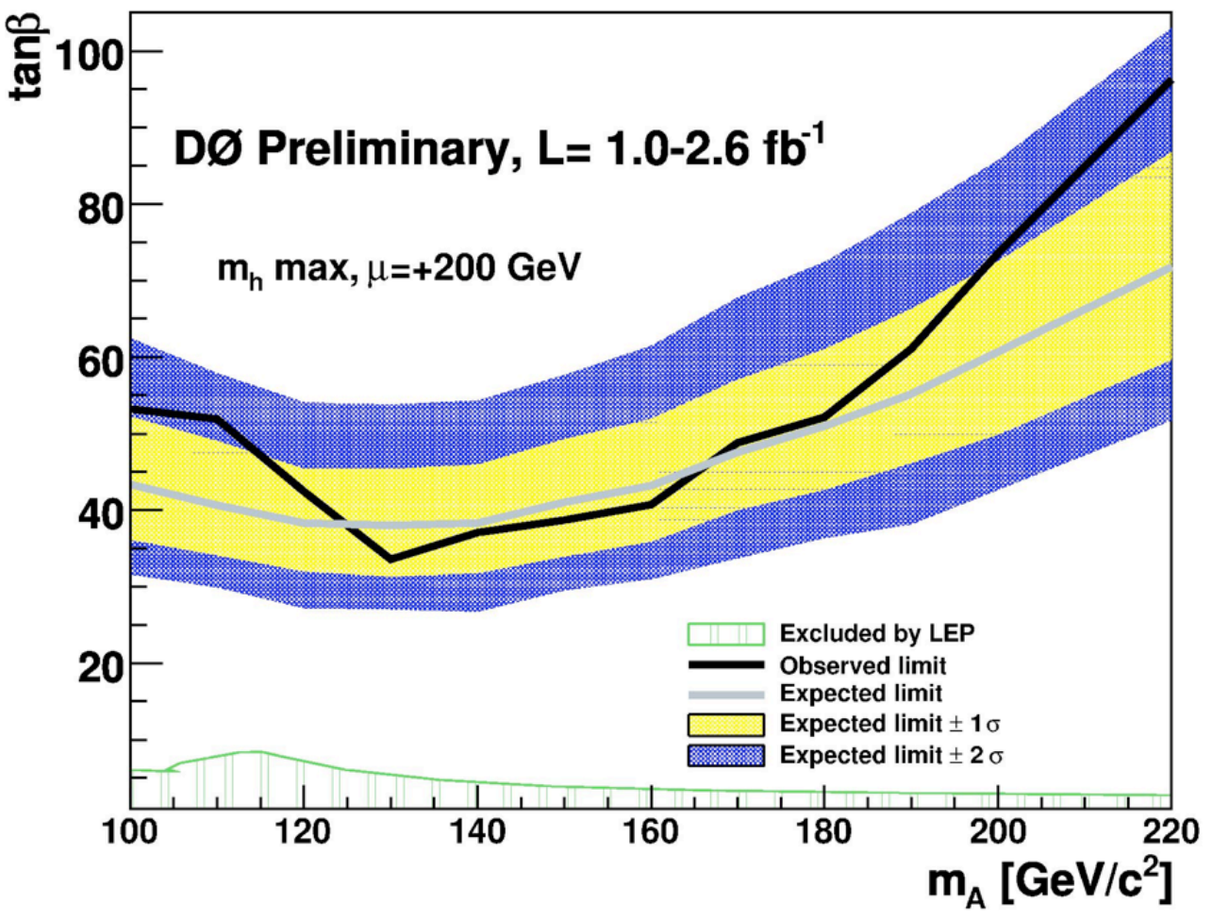
DØ combo: systematics

- Two types of systematics do exist:
  - affecting only the normalisation
  - affecting the variable shape

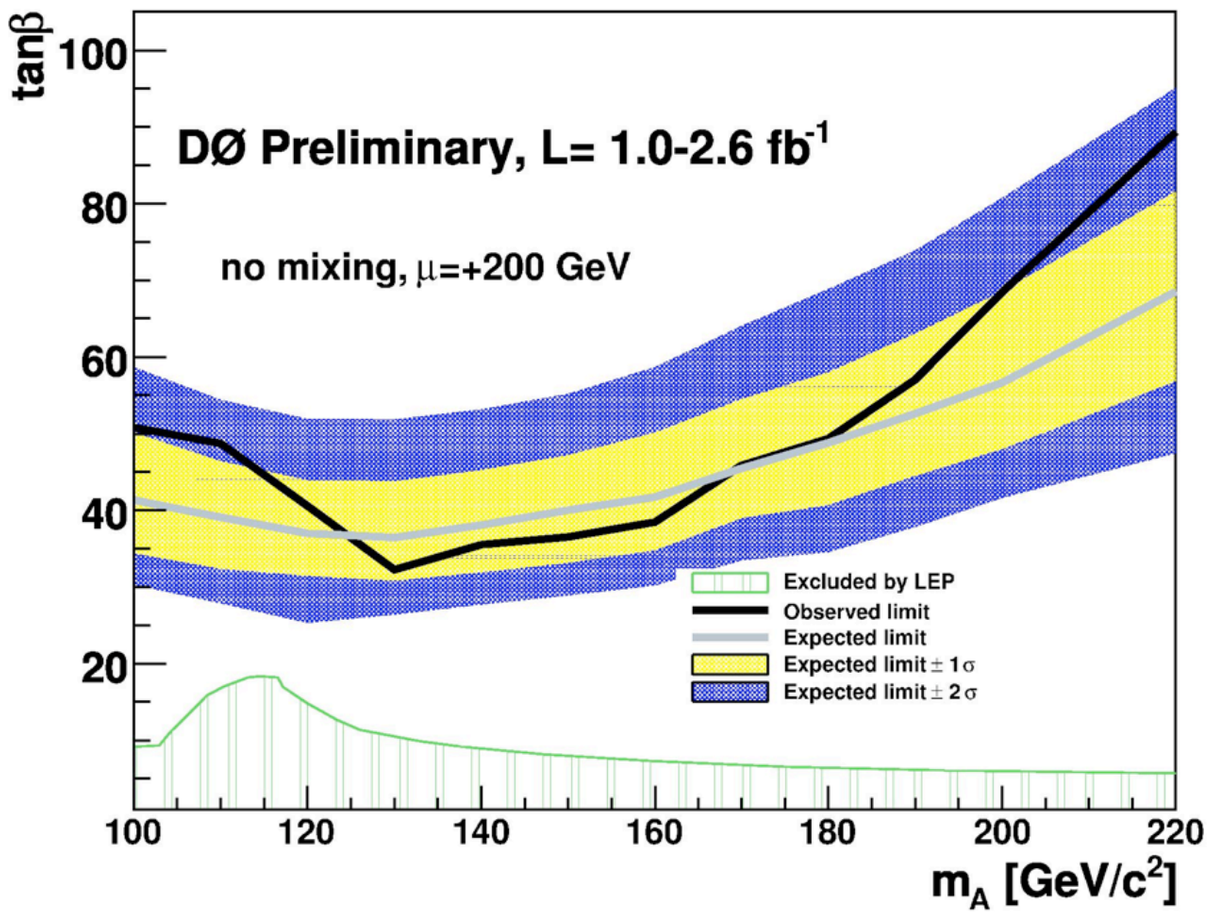
	RunIIa				RunIIb				
	$h \to \tau\tau$			$bh \to bb\bar{b}$	$h \to \tau\tau$	$bh \to b\tau\tau$	$bh \to bb\bar{b}$	Signal	Background
Source	$\tau_e\tau_\mu$	$\tau_e\tau_{\rm had}$	$\tau_\mu\tau_{\rm had}$		$\tau_\mu\tau_{\rm had}$	$\tau_\mu\tau_{\rm had}$		/%	/%
Luminosity	×	×	×	×	×	×	×	6.1	6.1
PDF	×	×	×	-	×	×	-	4	-
EM-Trigger	-	×	-	-	-	-	-	3-5	3-5
Muon Trigger	-	-	×	-	×	×	-	3-5	3-5
EM-Muon Trigger	×	-	-	-	-	-	-	3-4	3-4
EM-ID	×	×	-	-	-	-	-	3-8	3-8
Muon-ID	×	-	×	-	×	×	-	4-8	4-8
$\tau_{\rm had}$-ID	-	*	*	-	*	*	-	4-10	4-10
$\tau_{\rm had}$-energy scale (IIa)	-	*	*	-	-	-	-	2-4	2-4
$\tau_{\rm had}$-energy scale (IIb)	-	-	-	-	*	*	-	2-4	2-4
$\tau_{\rm had}$ track reconstruction	-	×	×	-	×	×	-	1-2	1-2
τ_μ track reconstruction	-	-	×	-	×	×	-	1-2	1-2
b-tagging	-	-	-	†	-	†	†	6-10	1-2
Jet energy scale and modelling	×	×	×	-	×	×	-	0.1-6	0.1-6
$W \to \mu\nu+$ jets	×	-	×	-	×	×	-	-	6-15
$Z \to ee$	-	×	-	-	-	-	-	-	5-13
Other MC background	×	×	×	-	×	-	-		5
Heavy flavour MC	-	-	-	-	-	×	-	-	50
bbb and bbj modelling	-	-	-	†	-	-	†	-	s
Multi-jet backgrounds		†	†	†	†	†	†	-	4-47

DØ combo: limits

- Most stringent limits to date at hadron collider
- Reaching the interesting region of $\tan\beta \approx 40$



m_h-max scenario

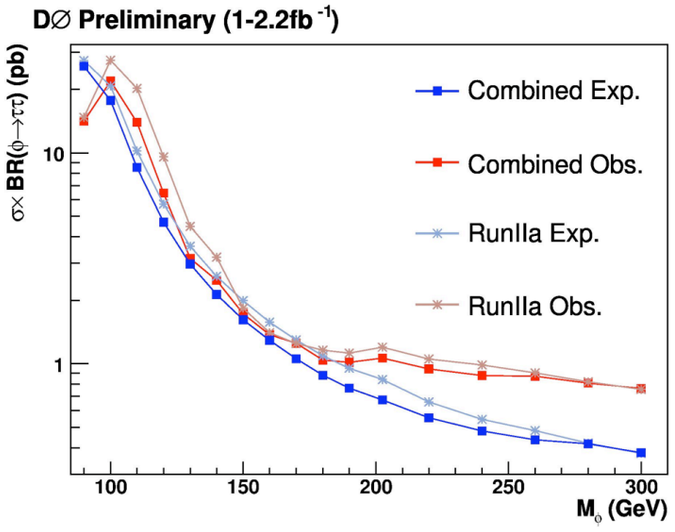


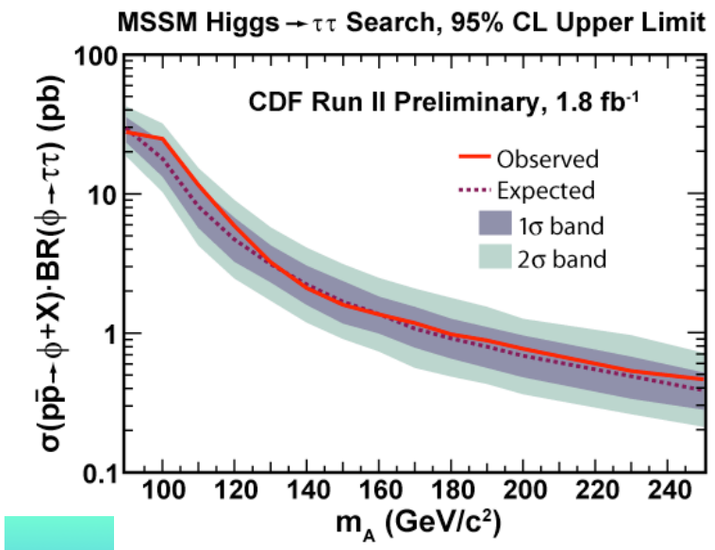
no mixing scenario

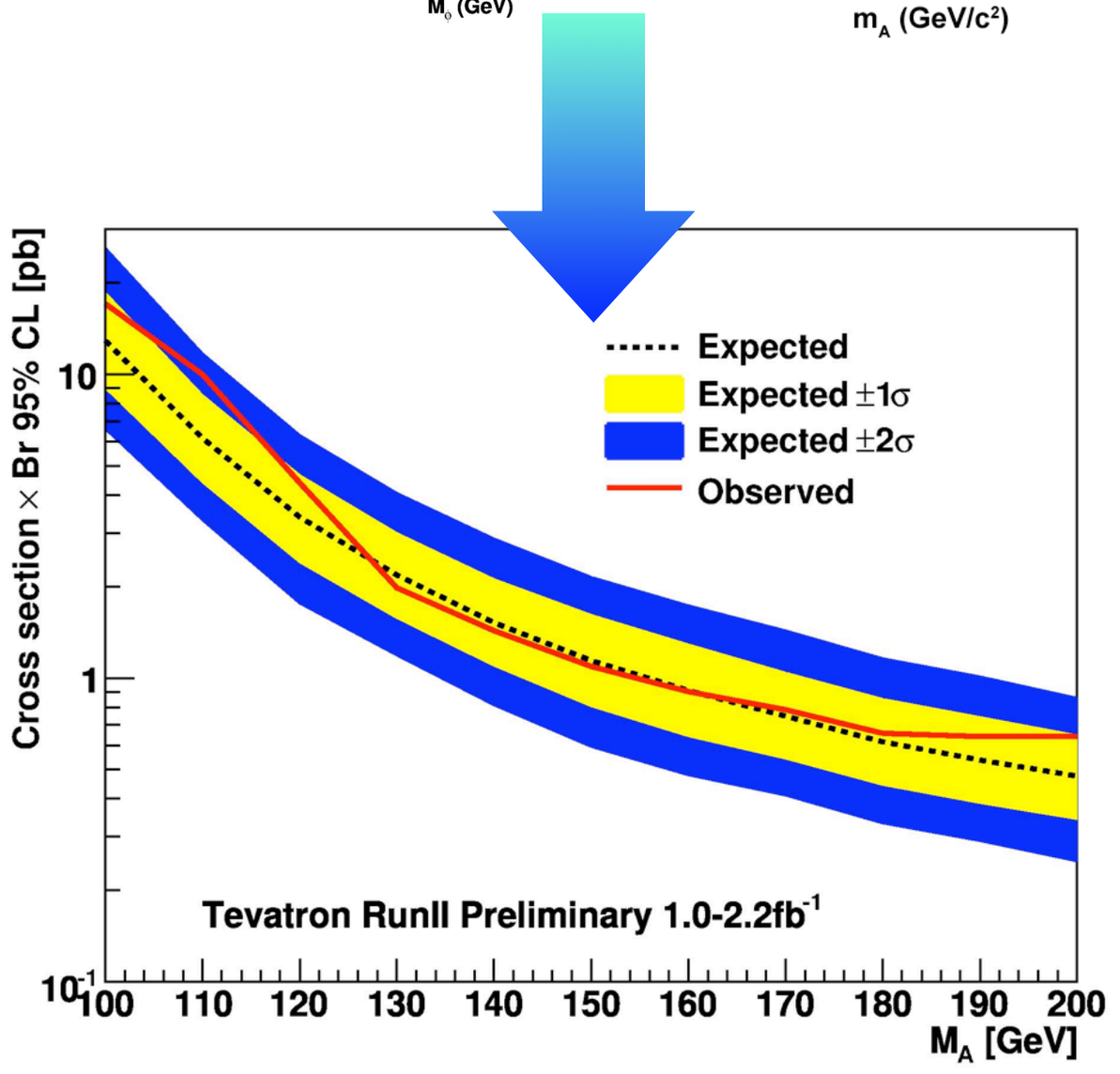
DØ - CDF combination

TeVatron combination

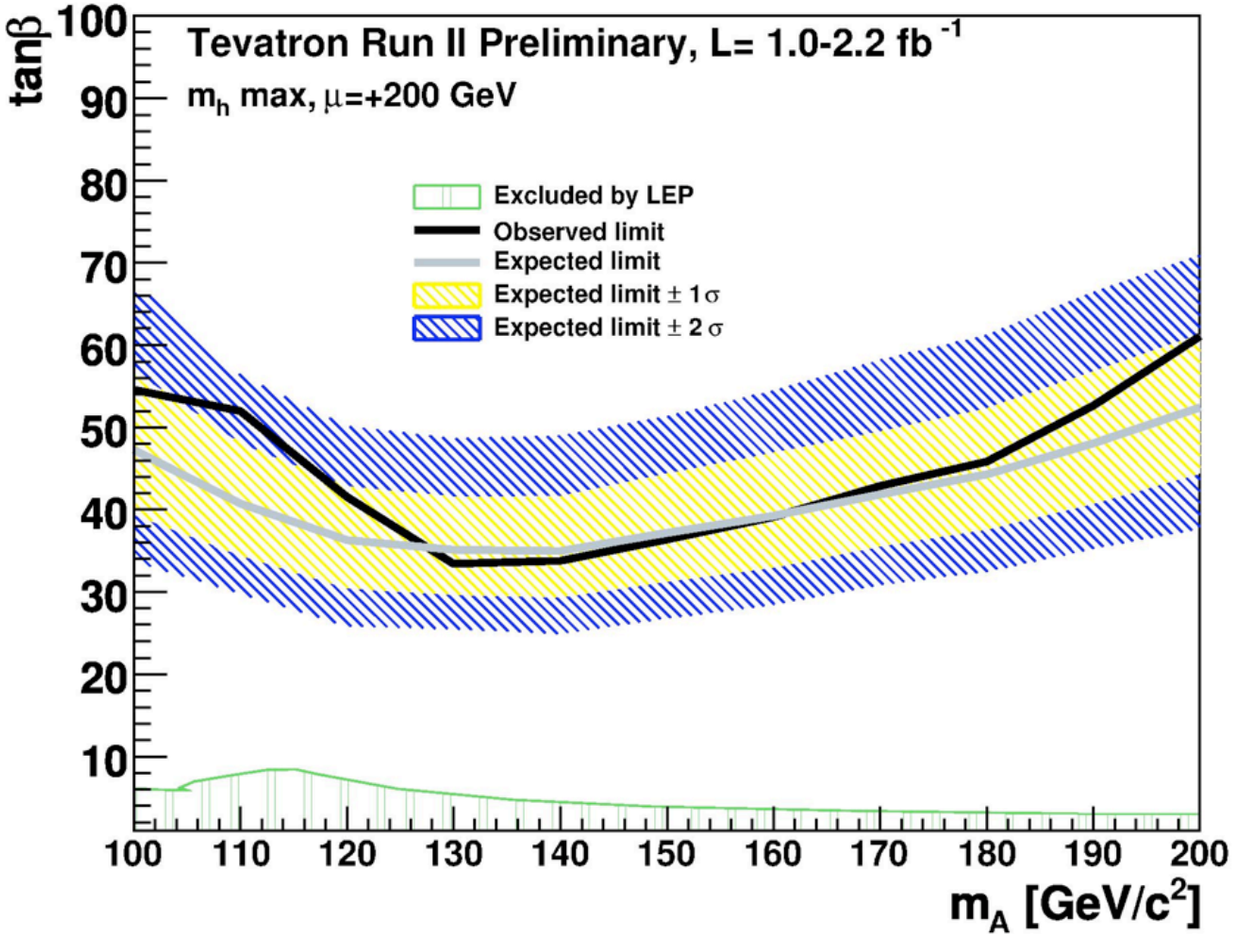
- ✓ $\tau_\mu\tau_h$, $\tau_e\tau_h$, $\tau_e\tau_\mu$
- ✓ CDF: 1.8 fb^{-1}
- ✓ DØ: 1.0 to 2.2 fb^{-1}
- ✓ Combo done with 2 different methods: Bayesian and Modified frequentist. Results consistent within 10%.
- ✓ Model independent limit!



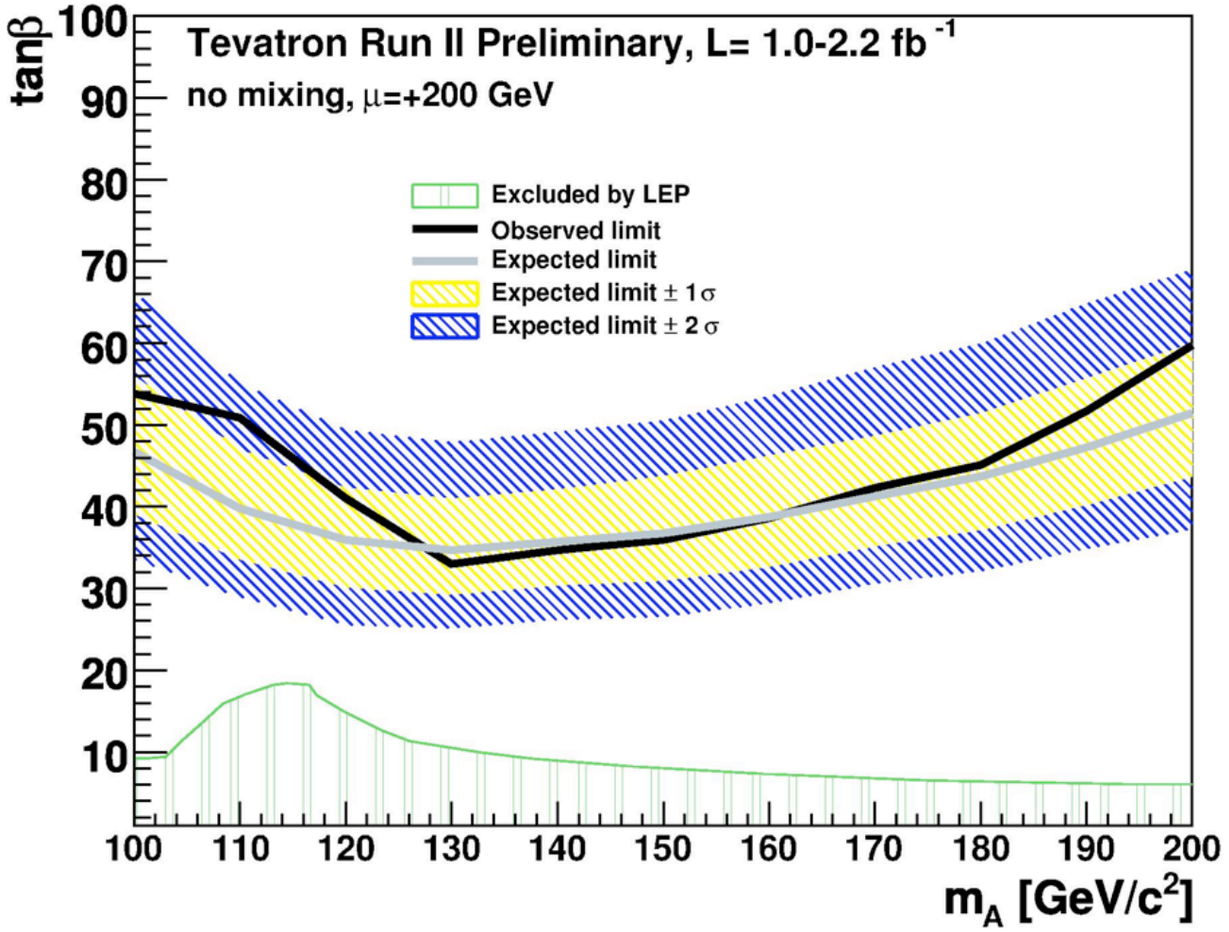




m_h max scenario



no mixing scenario



Charged Higgs searches

Principle

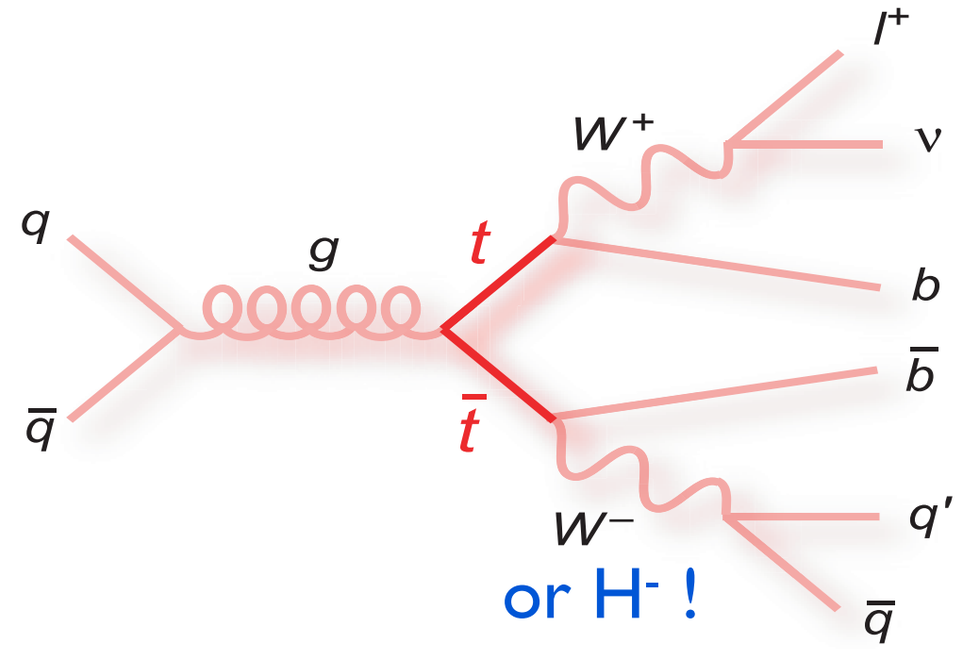
- If $m_{H+} < m_{top}$:

  $t \rightarrow H^+ b$ opens

- H^+ decays are very different from W^+ decays:

  ✓ high tanβ: $B(H^+ \rightarrow \tau\, \upsilon) = 1$

  ✓ leptophobic: $B(H^+ \rightarrow c\, \bar{s}) = 1$



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- If $m_{H+} < m_{top}$:

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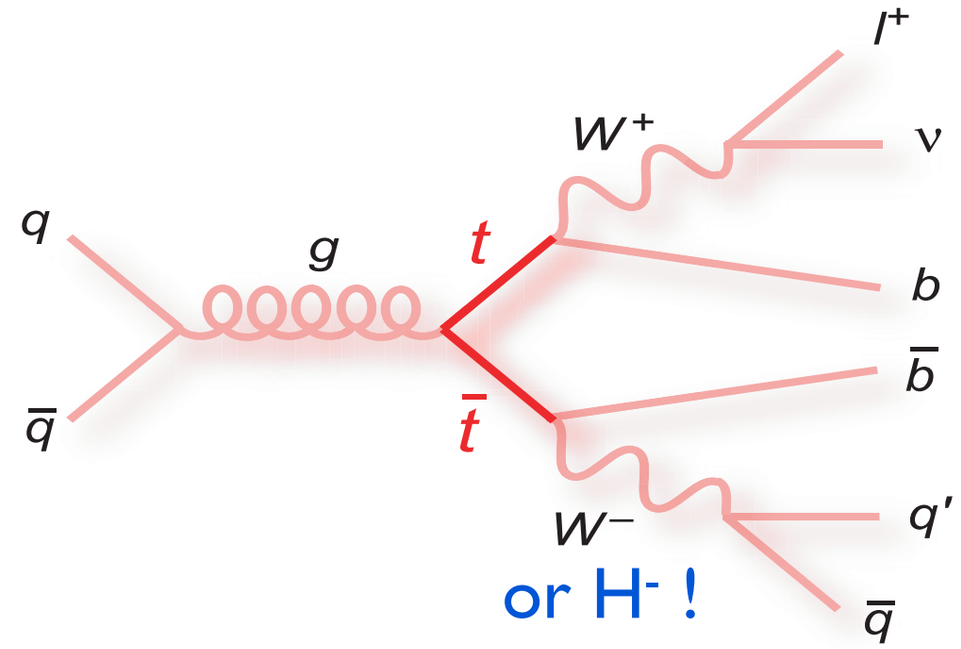
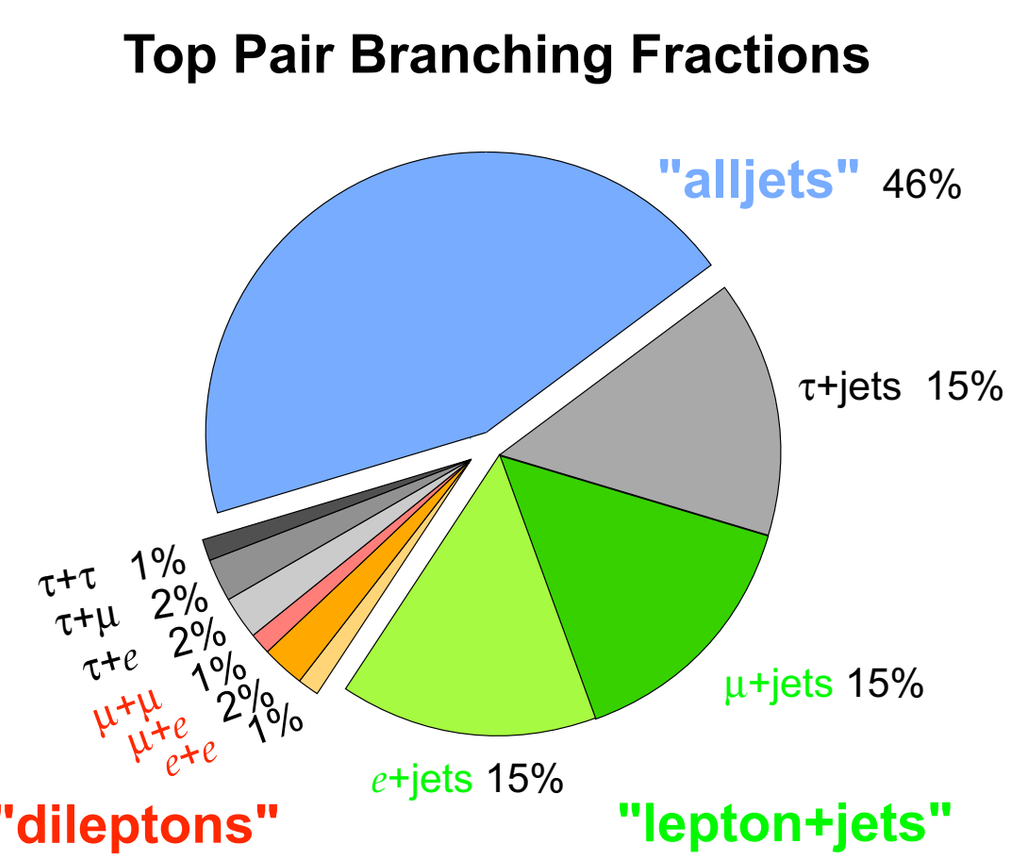


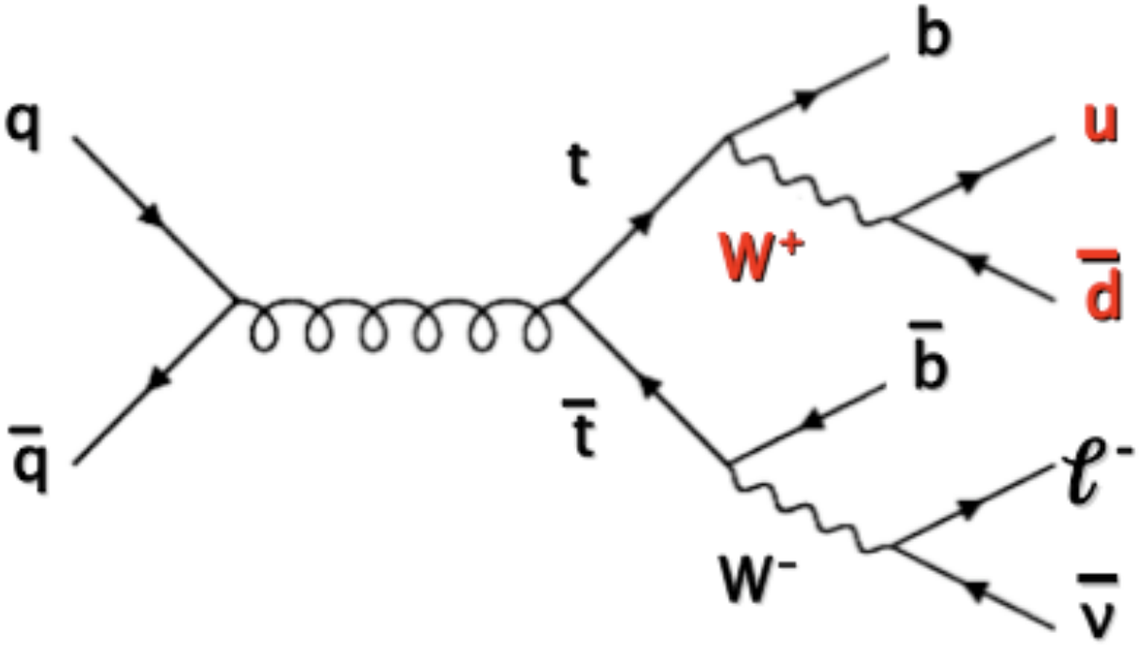
- H^+ decays are very different from W^+ decays:

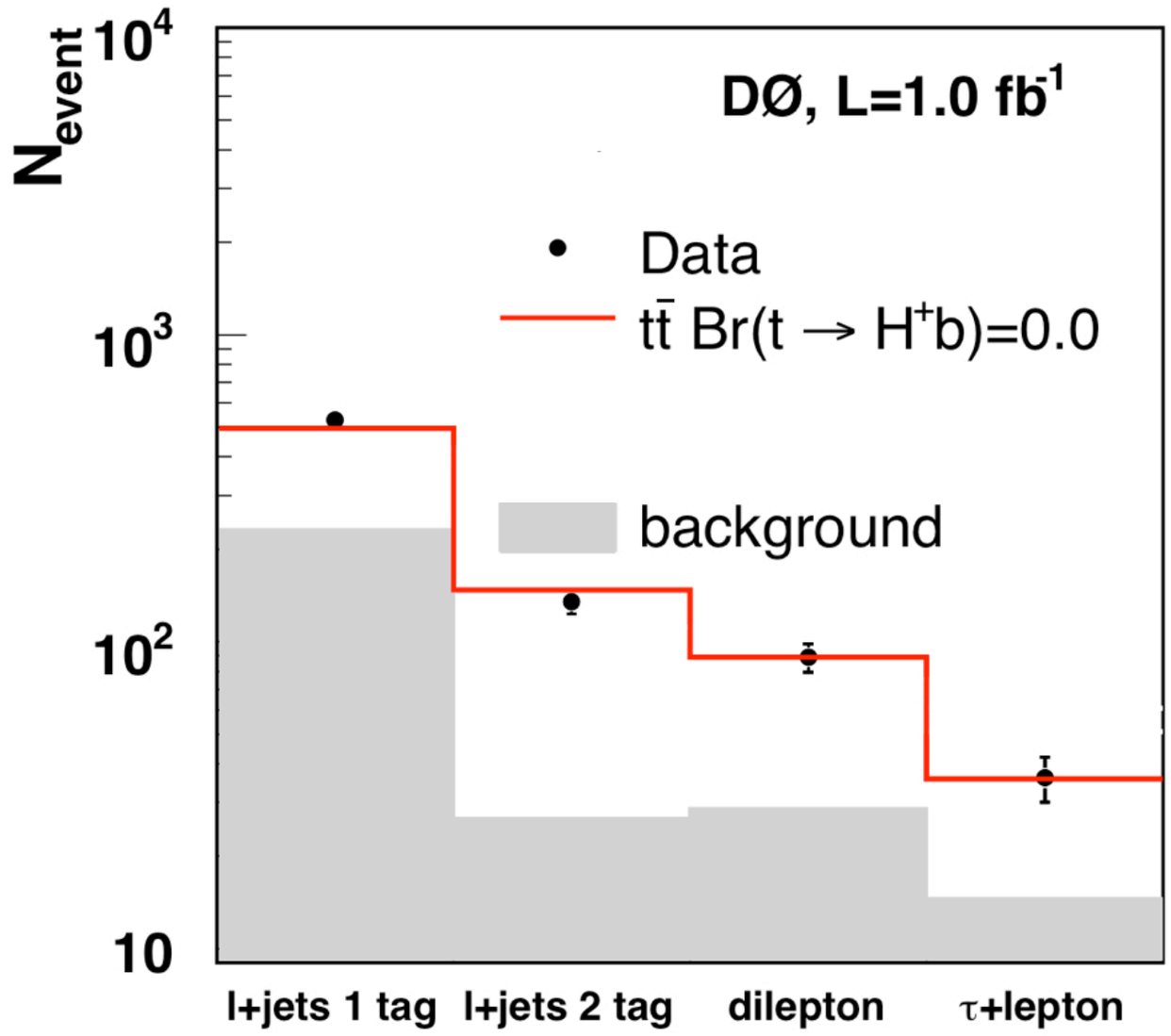
  ✓ high tanβ: $B(H^+ \rightarrow \tau\, \upsilon) = 1$

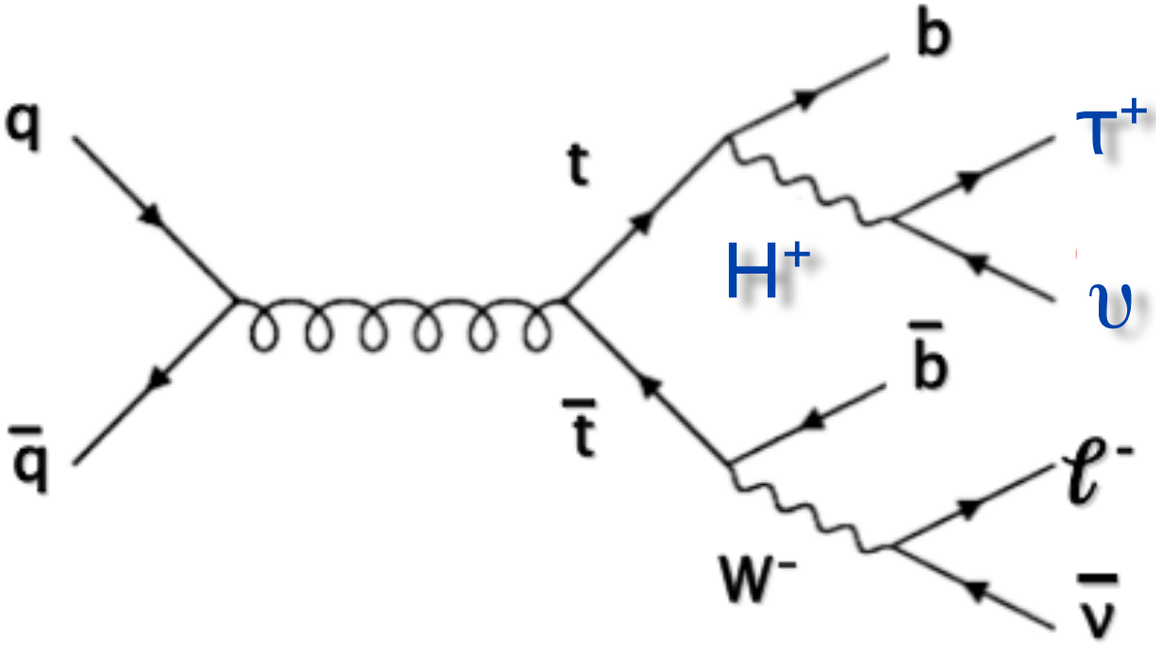
  ✓ leptophobic: $B(H^+ \rightarrow c\, \bar{s}) = 1$

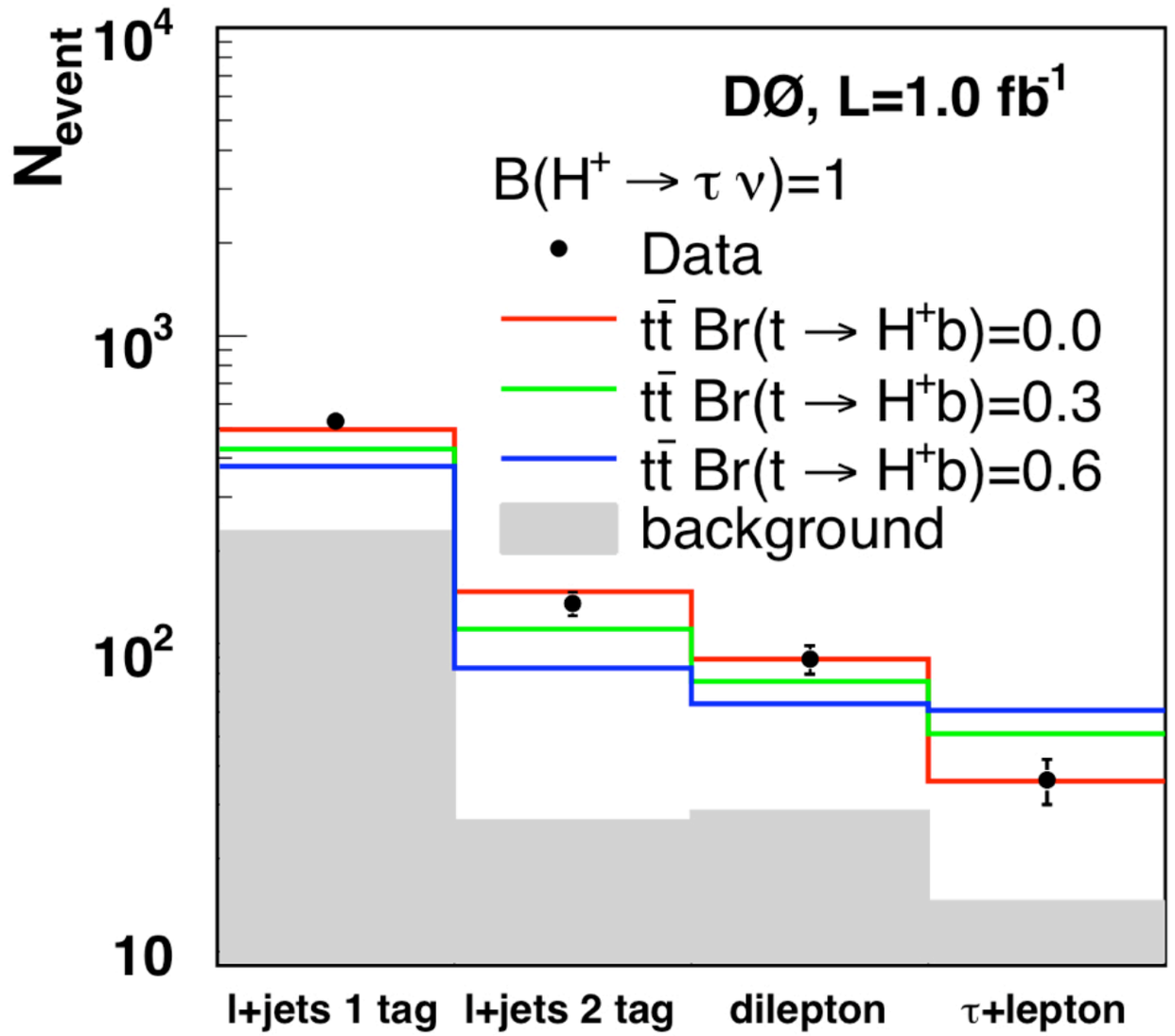
- Changes the different channels contributions: compare all the measured cross sections



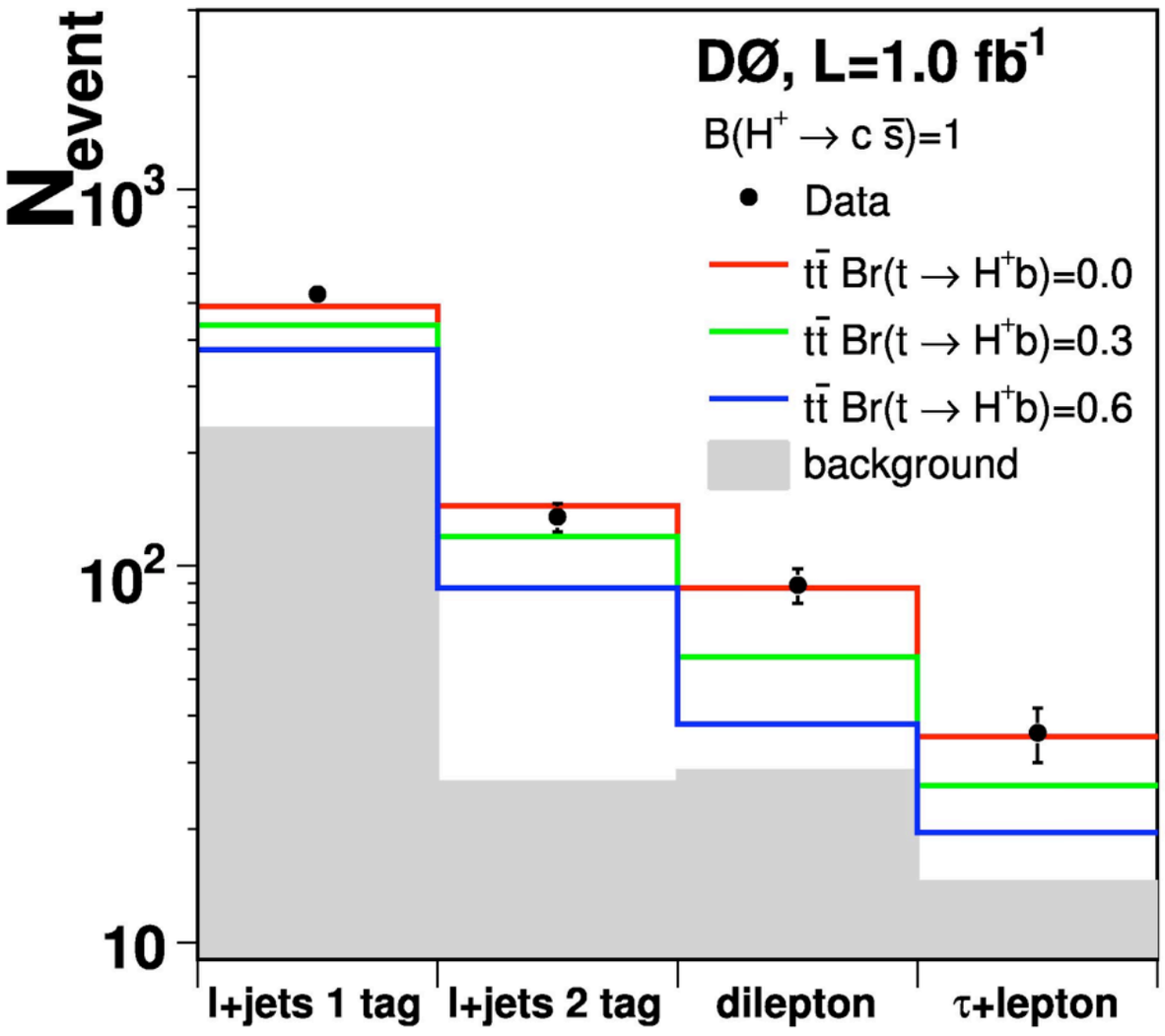

q
$\bar{q}$
t
$\bar{t}$
b
u
W^+
$\bar{d}$
$\bar{b}$
ℓ^-
W^-
$\bar{\nu}$


N_{event}
10^4
10^3
10^2
10
DØ, L=1.0 fb^{-1}
Data
$t\bar{t}$ Br(t → H^+b)=0.0
background
l+jets 1 tag
l+jets 2 tag
dilepton
τ+lepton

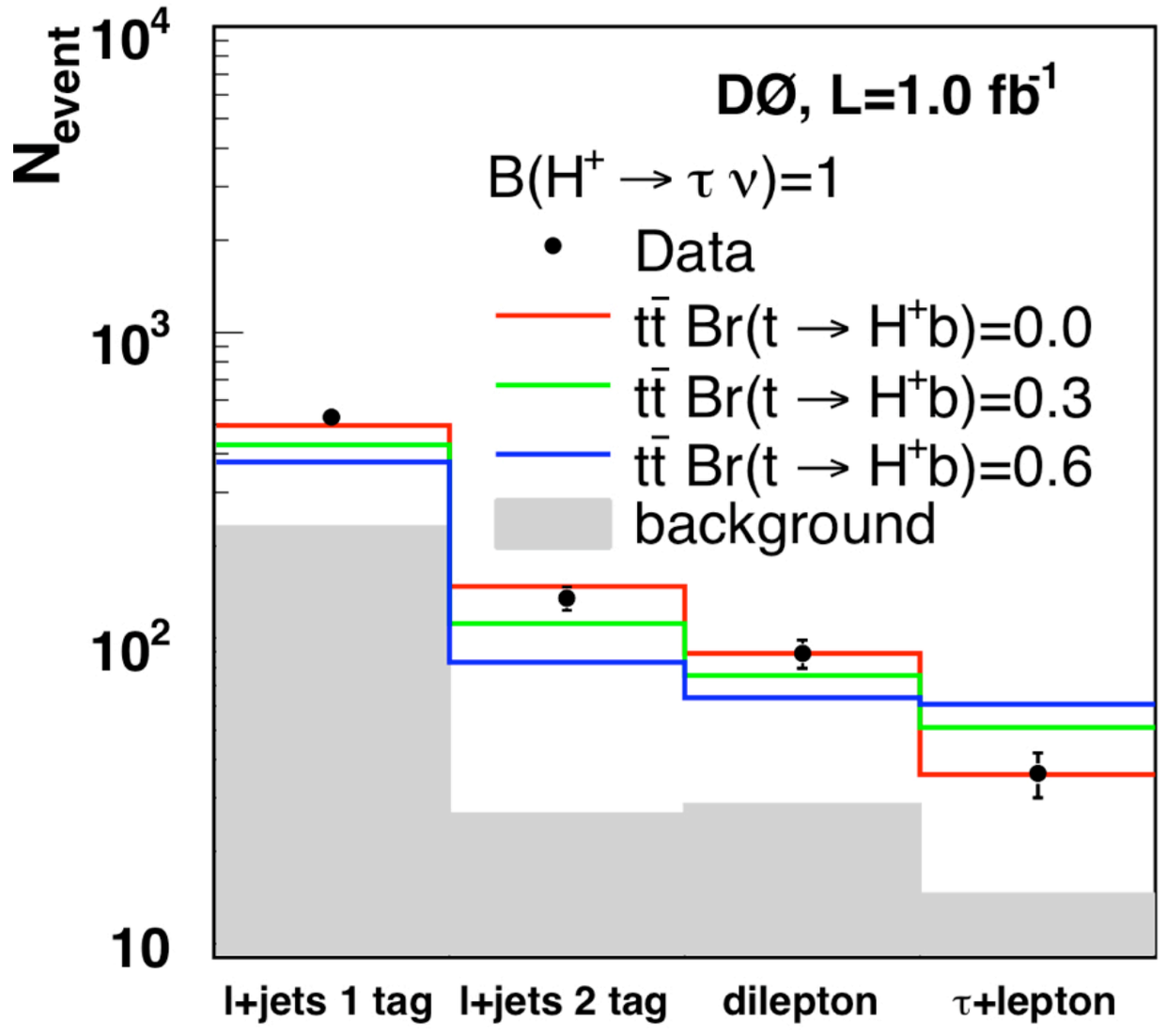

q
$\bar{q}$
t
$\bar{t}$
b
$\bar{b}$
H^+
τ^+
υ
W^-
ℓ^-
$\bar{\nu}$


N_{event}
10^4
10^3
10^2
10
DØ, L=1.0 fb^{-1}
B($H^+ \rightarrow \tau\ \nu$)=1
Data
$t\bar{t}$ Br($t \rightarrow H^+b$)=0.0
$t\bar{t}$ Br($t \rightarrow H^+b$)=0.3
$t\bar{t}$ Br($t \rightarrow H^+b$)=0.6
background
l+jets 1 tag
l+jets 2 tag
dilepton
τ+lepton

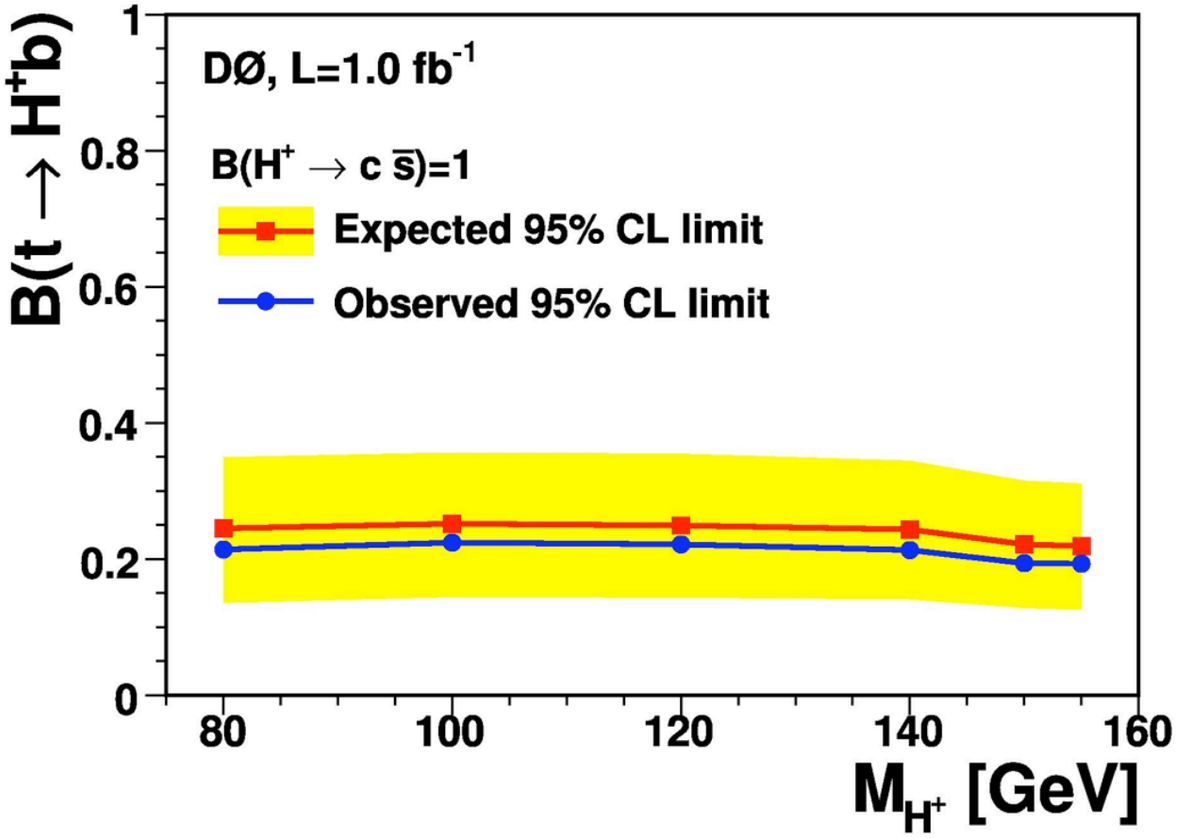
leptophobic Higgs



tauonic Higgs

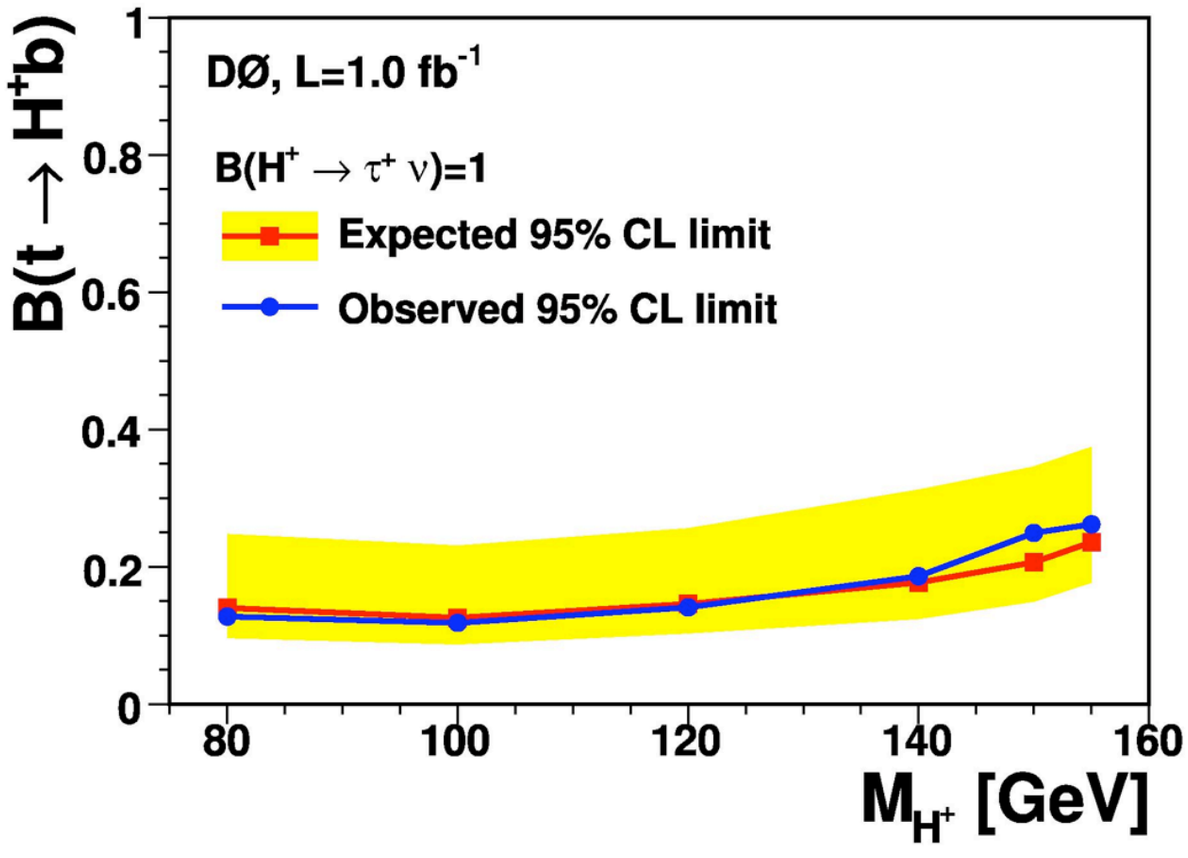


Limits on $\mathcal{B}(t \to bH)$

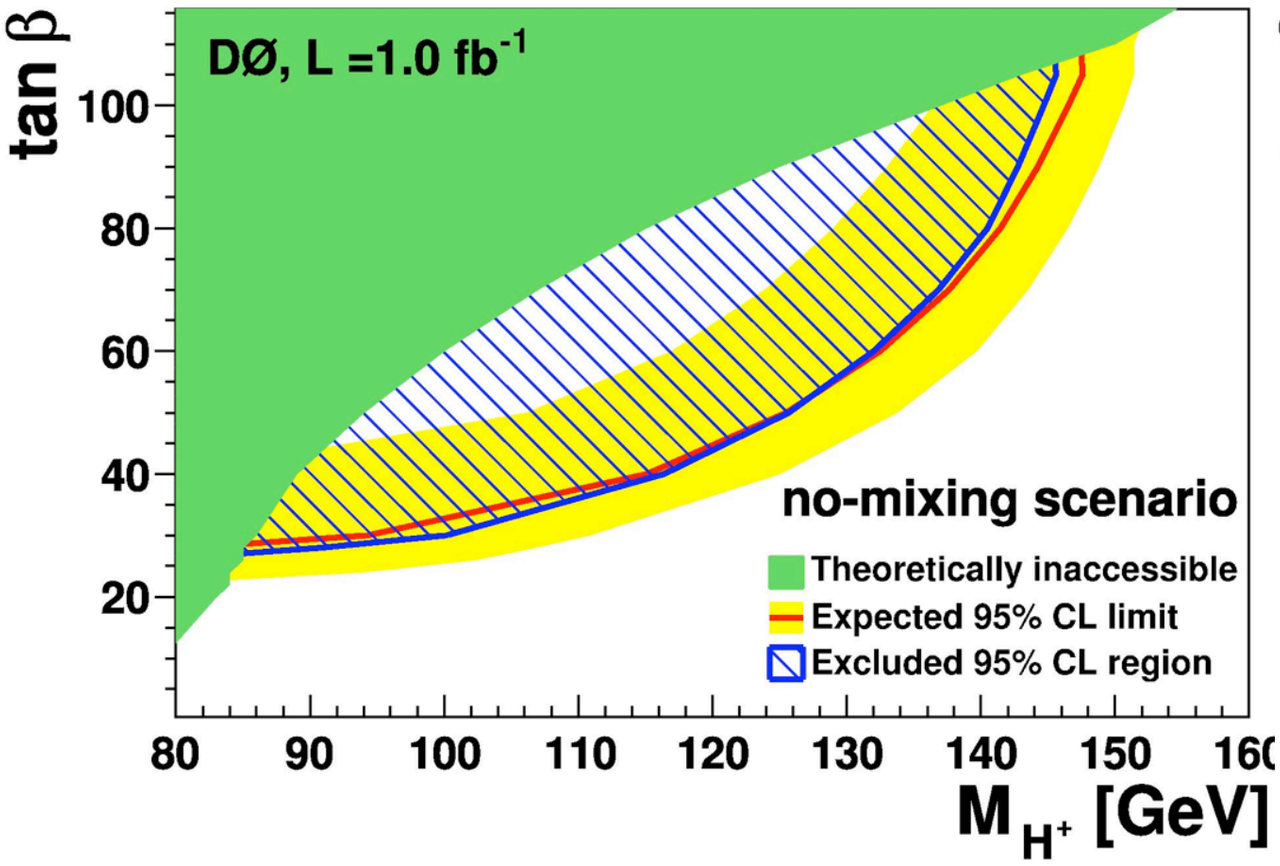


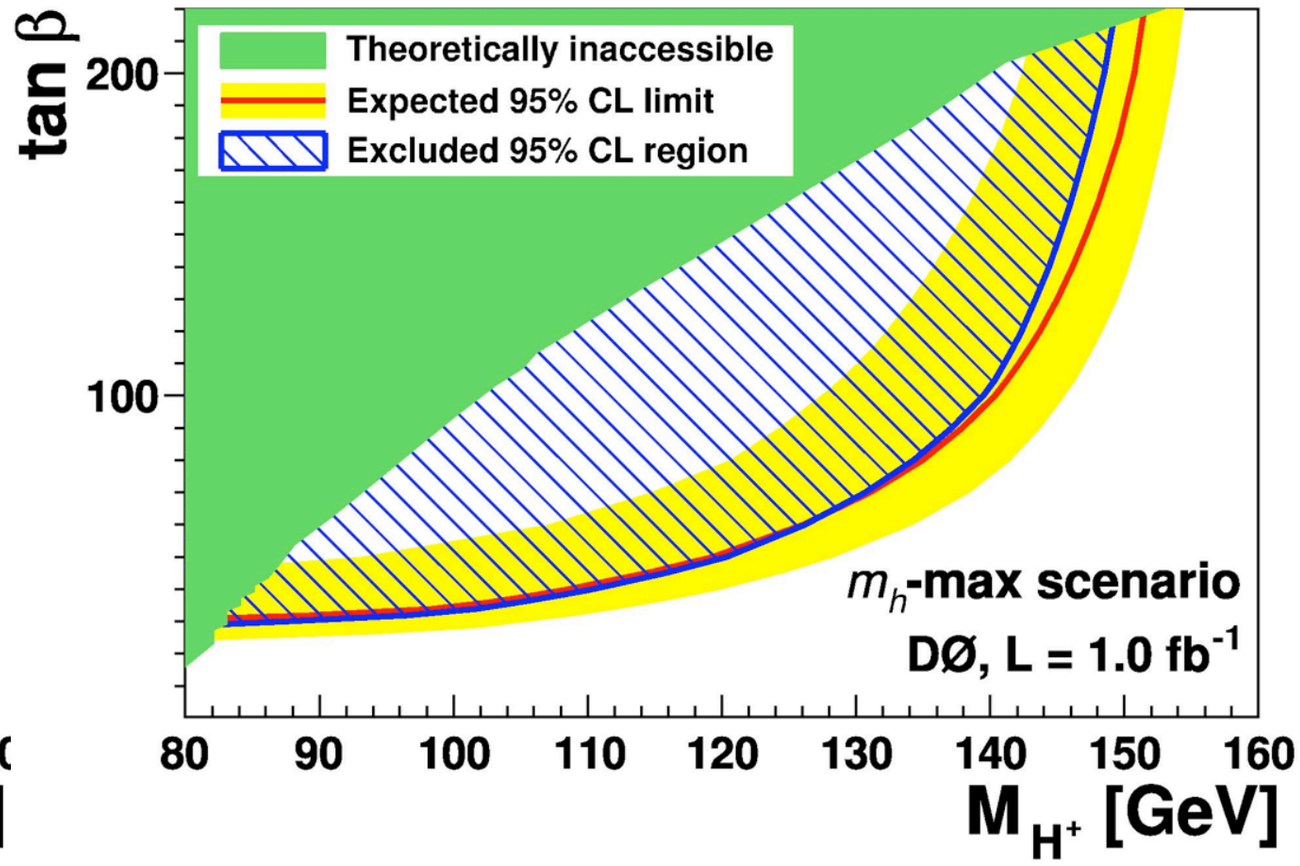
Fix σ_{tt} to its theoretical value in the fit

Let σ_{tt} float in the fit



MSSM interpretation



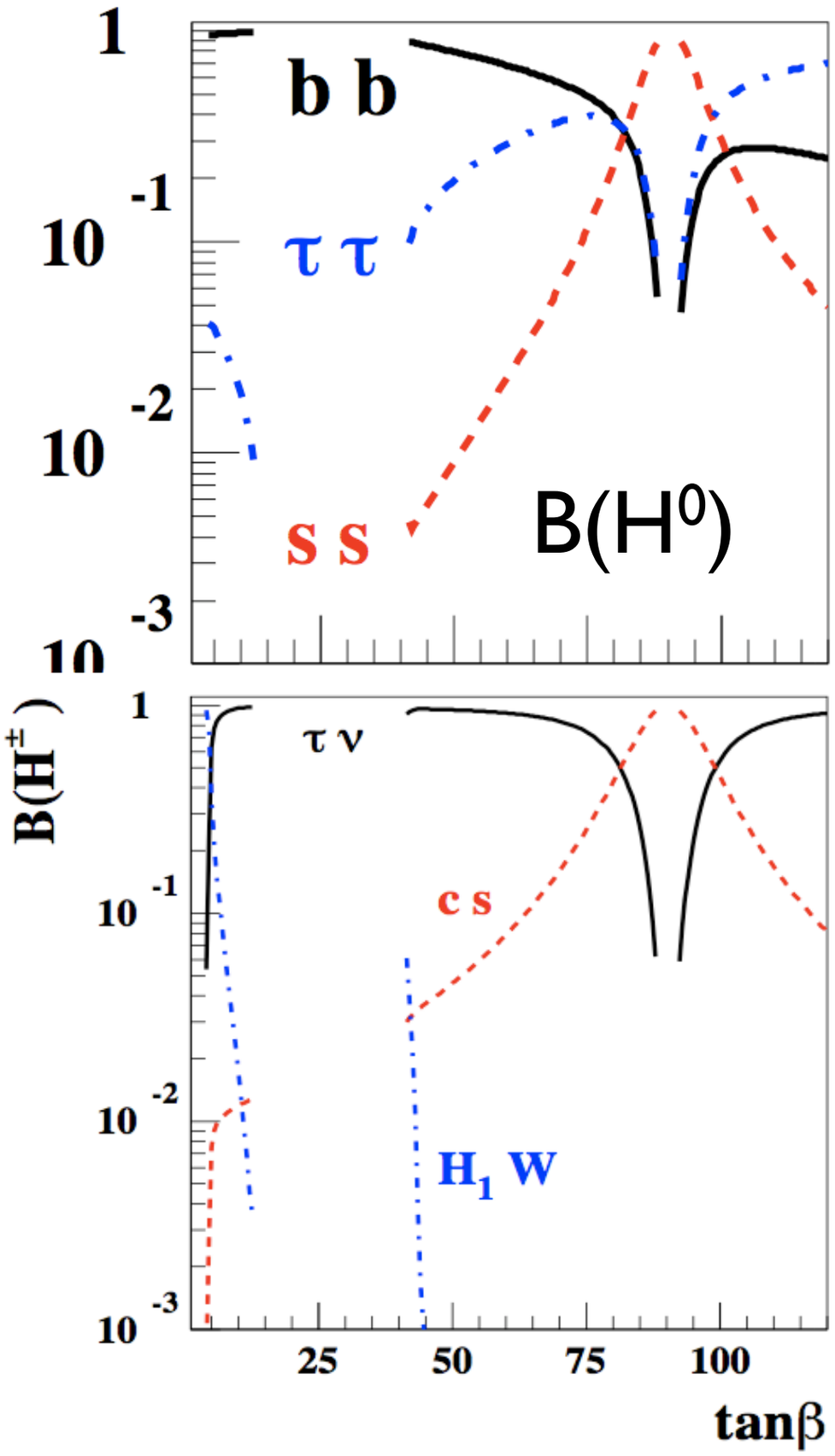


arXiv:0908.1811, submitted to PLB

method based only on cross section ratios:
arXiv:0903.5525, submitted to PLB

Another strategy:
The topological method
PRL 102, 191802 (2009)

CPX scenario

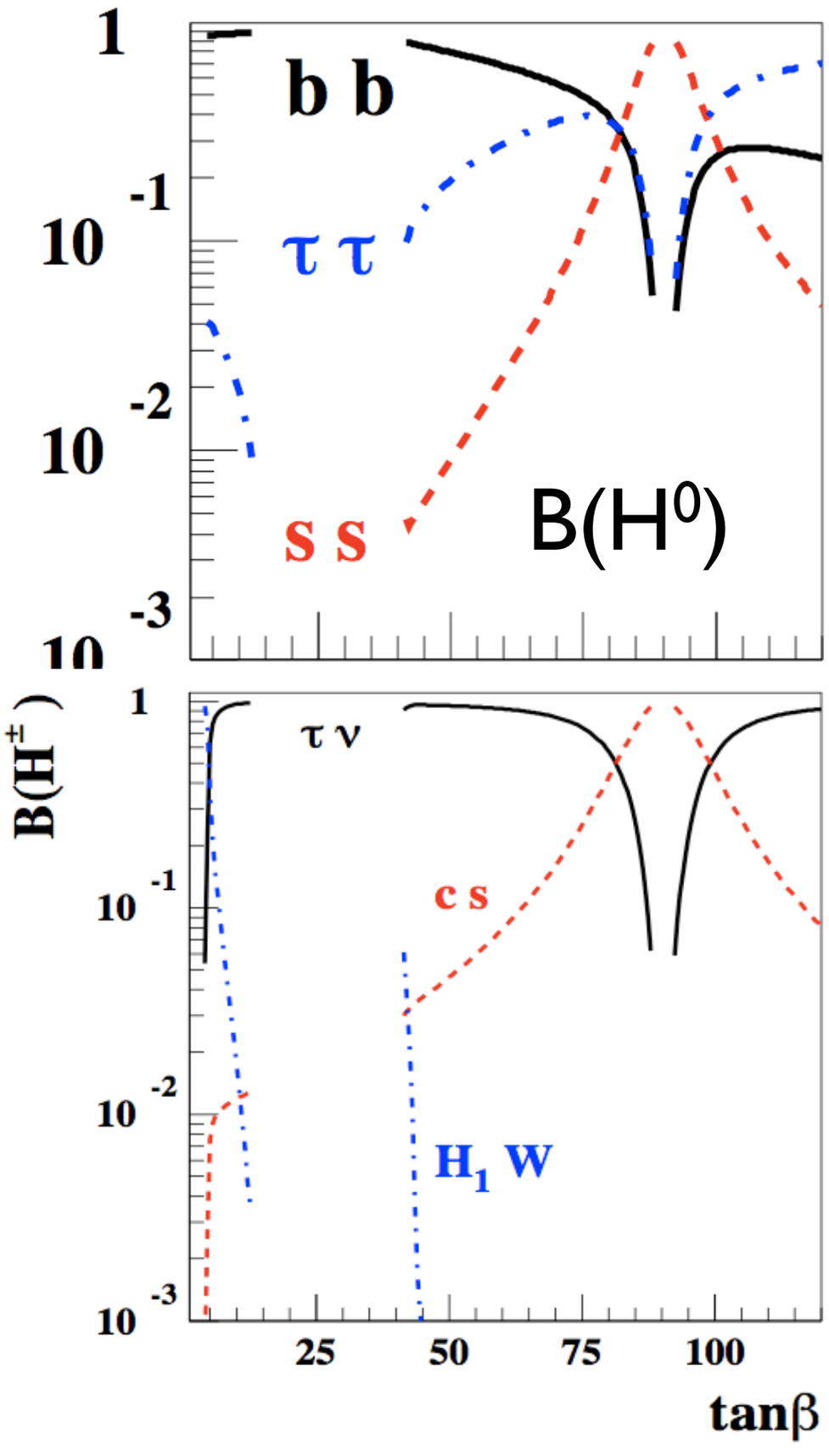


CPX benchmark scenario:

- coupling to s-quark dramatically enhanced compare to b
- strangephilic Higgs bosons
- $B(H^+ \rightarrow cs) \approx 1$

Lee, Peters, Pilaftsis,and C. Schwanenberger, arXiv:0909.1749

CPX scenario



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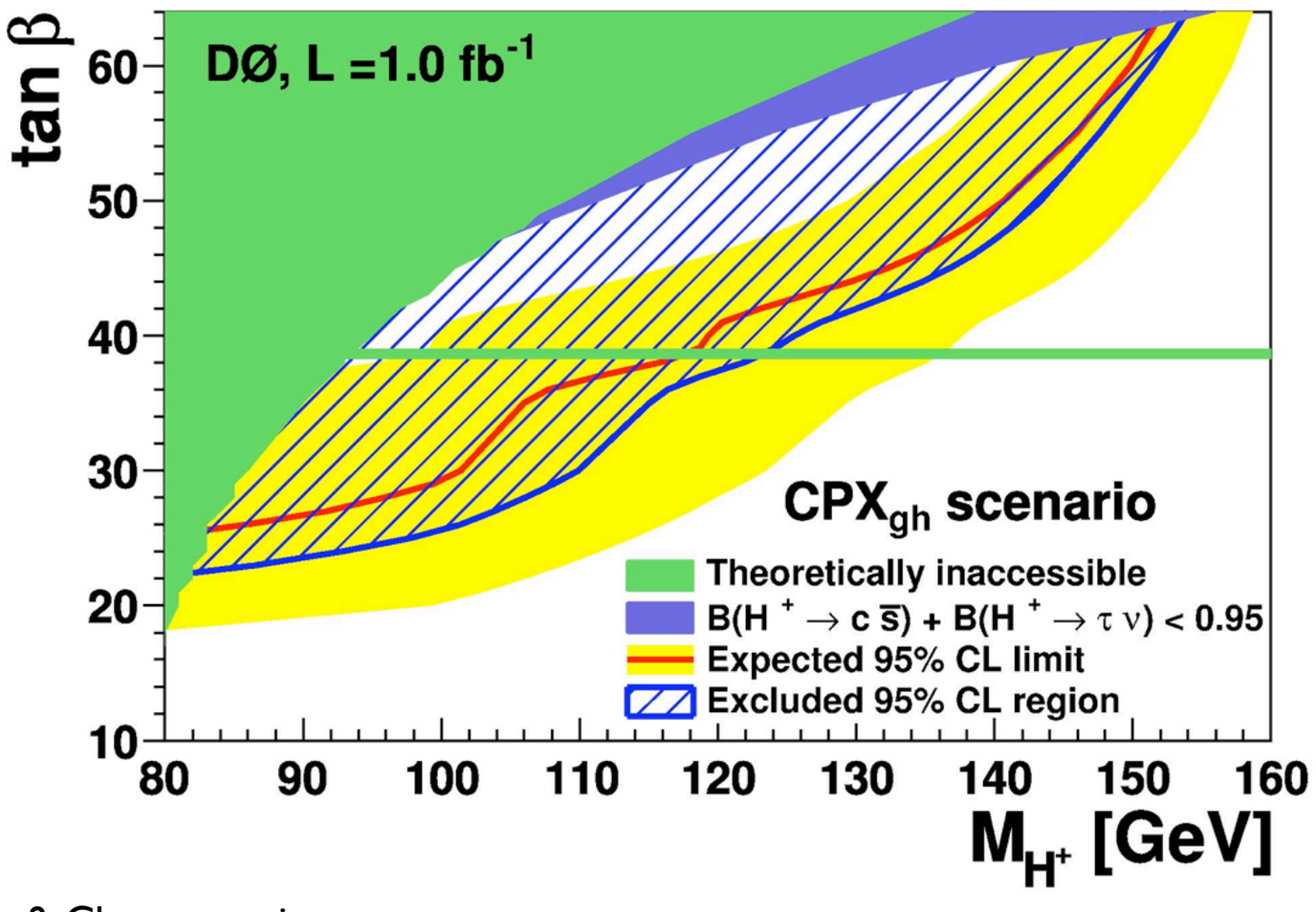
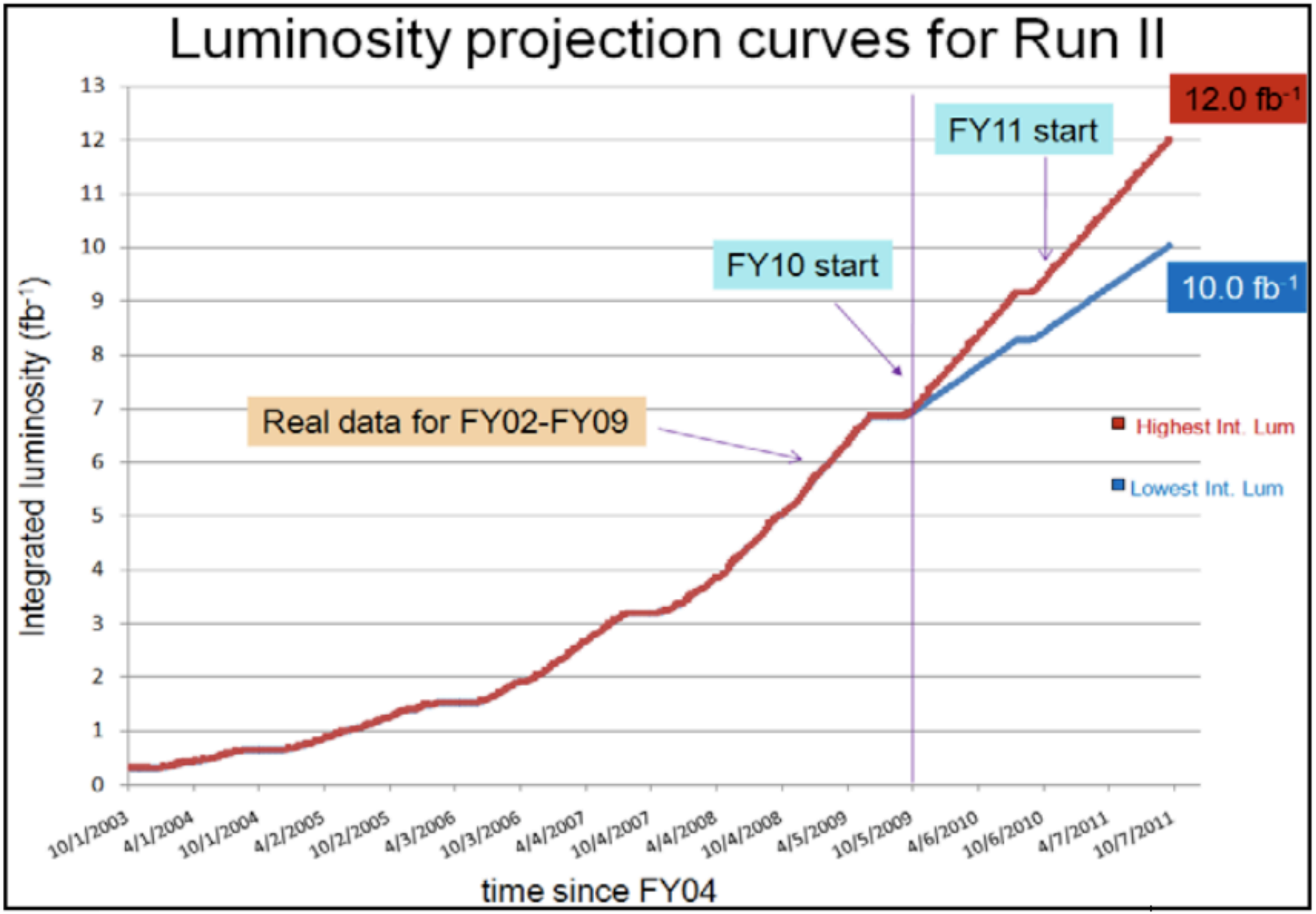


Prospects

Luminosity projection

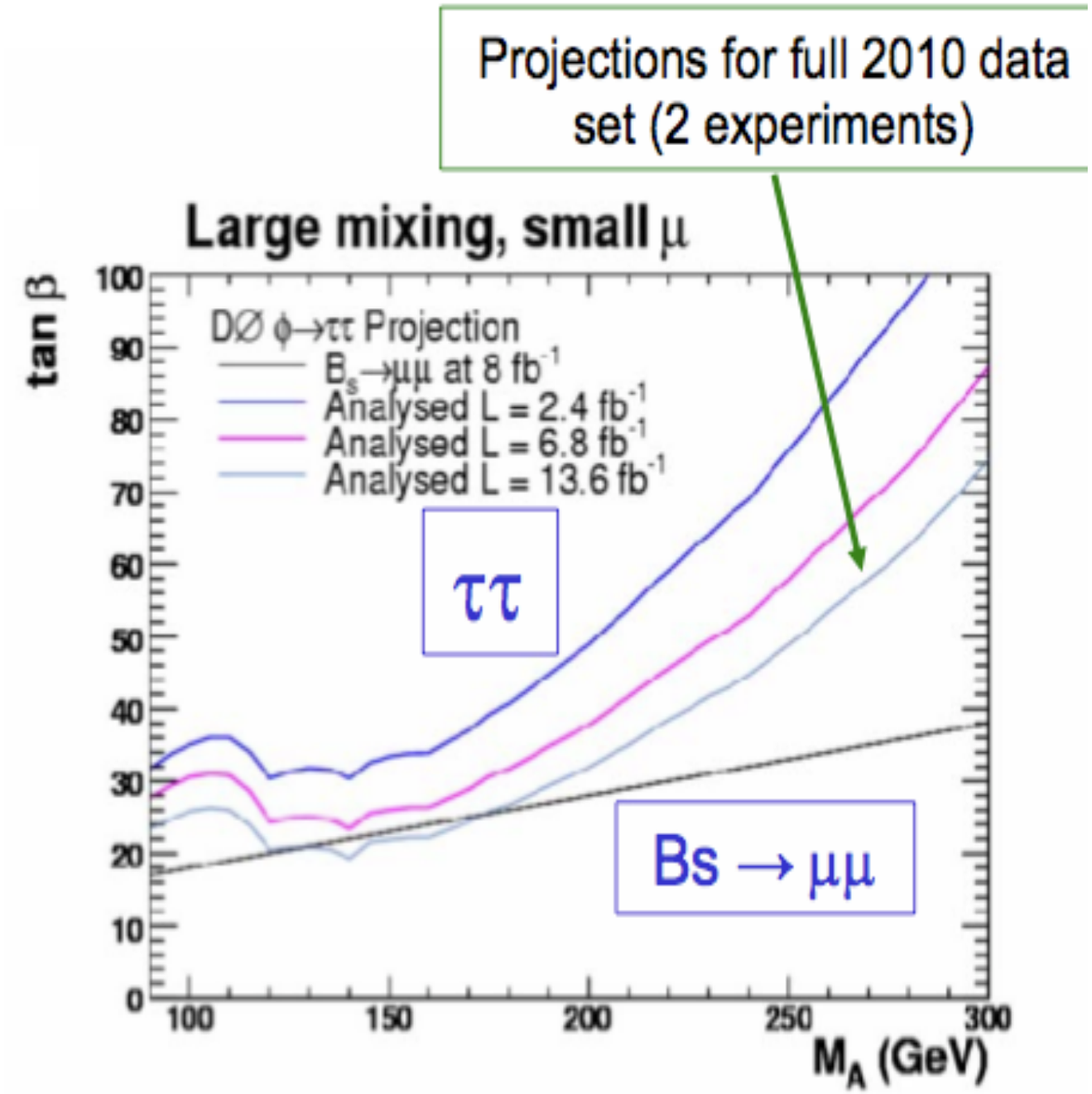


Usual MSSM channels

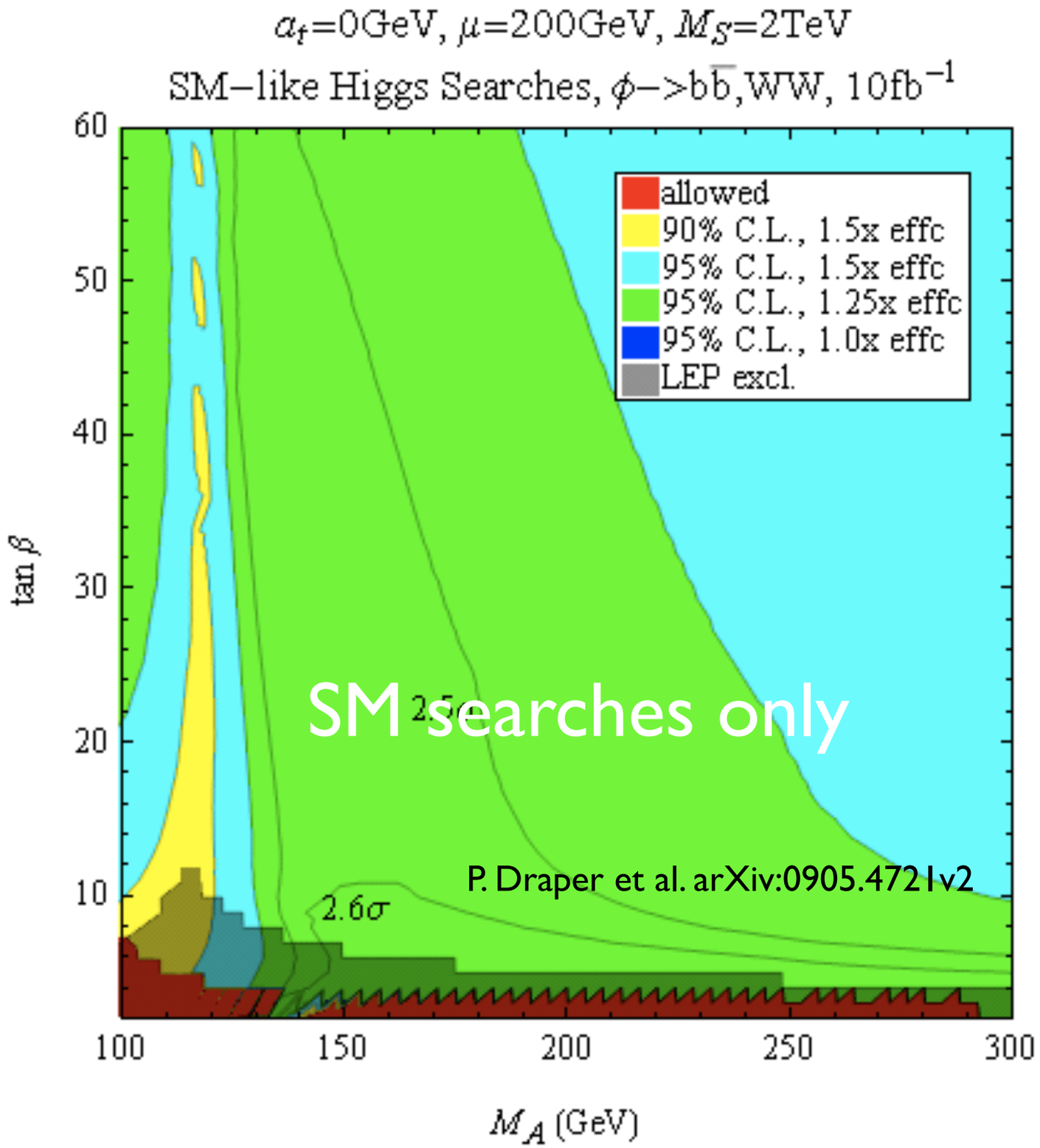
- Already probing an interesting region of the MSSM phase space.
- 6 fb^{-1} already recorded on tape (at most 2.6fb^{-1} in this talk)

Potential improvements

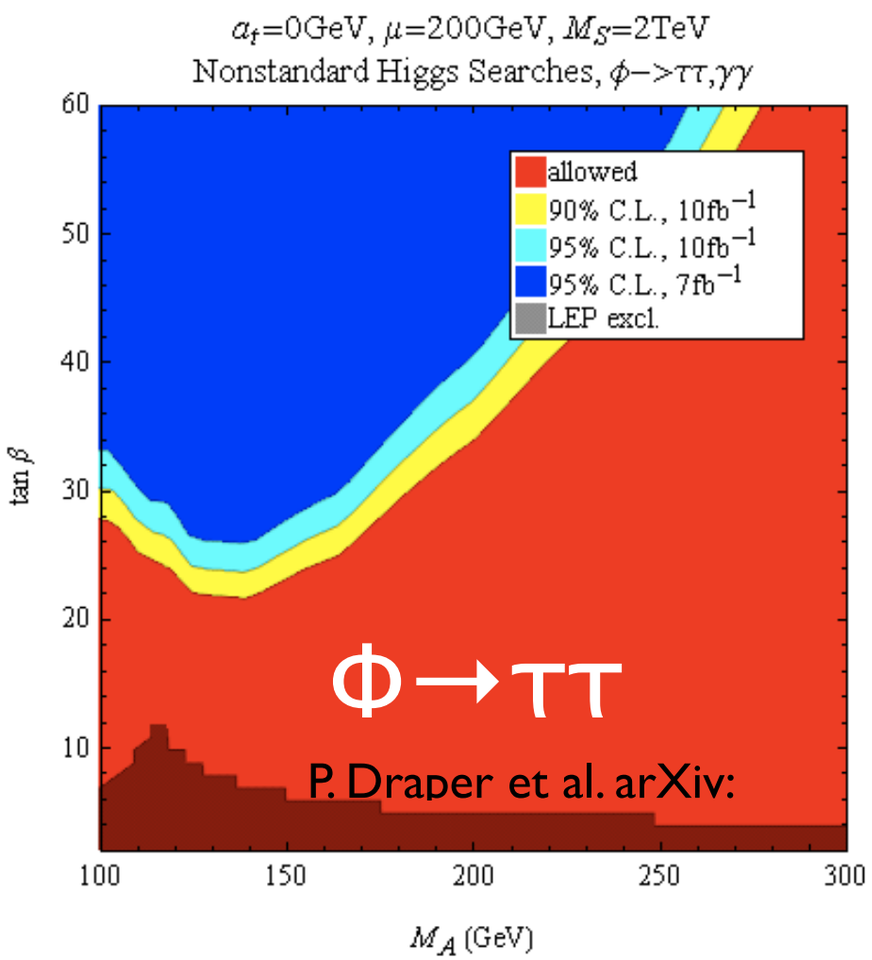
- Add statistics
- Add some more channels:
  - ✓ $b\Phi \rightarrow b\tau_e\tau_h$
  - ✓ H^+ searches
- full combination with CDF
- Recycle SM Higgs searches



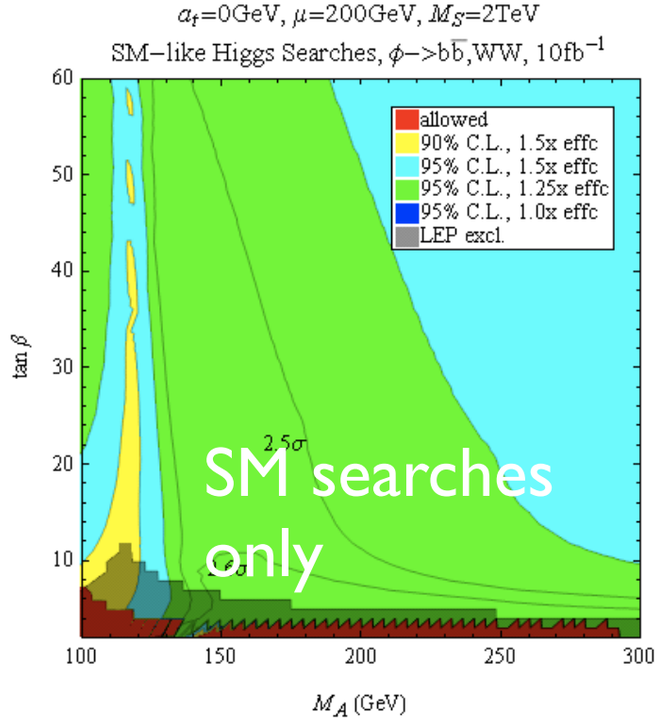
- SM searches can be used as well:
  - h has SM like couplings on a large portion of the MSSM phase space
  - H becomes increasingly SM-like when M_A decreases.
  - based on the work by P. Draper et al. arXiv:0905.4721v2:
    - they consider SM Higgs exclusion and translate it into MSSM constraints for 4 MSSM scenarii
    - furthermore they combined with $\Phi \rightarrow \tau\tau$ searches
    - use 10 fb^{-1} + improvements in SM anlysis (25%)


a_t=0GeV, μ=200GeV, M_S=2TeV
SM−like Higgs Searches, ϕ−>b$\bar{b}$,WW, 10fb^{-1}
allowed
90% C.L., 1.5x effc
95% C.L., 1.5x effc
95% C.L., 1.25x effc
95% C.L., 1.0x effc
LEP excl.
SM searches only
P. Draper et al. arXiv:0905.4721v2
2.6σ
2.5σ
tan β
M_A (GeV)
60
50
40
30
20
10
100
150
200
250
300

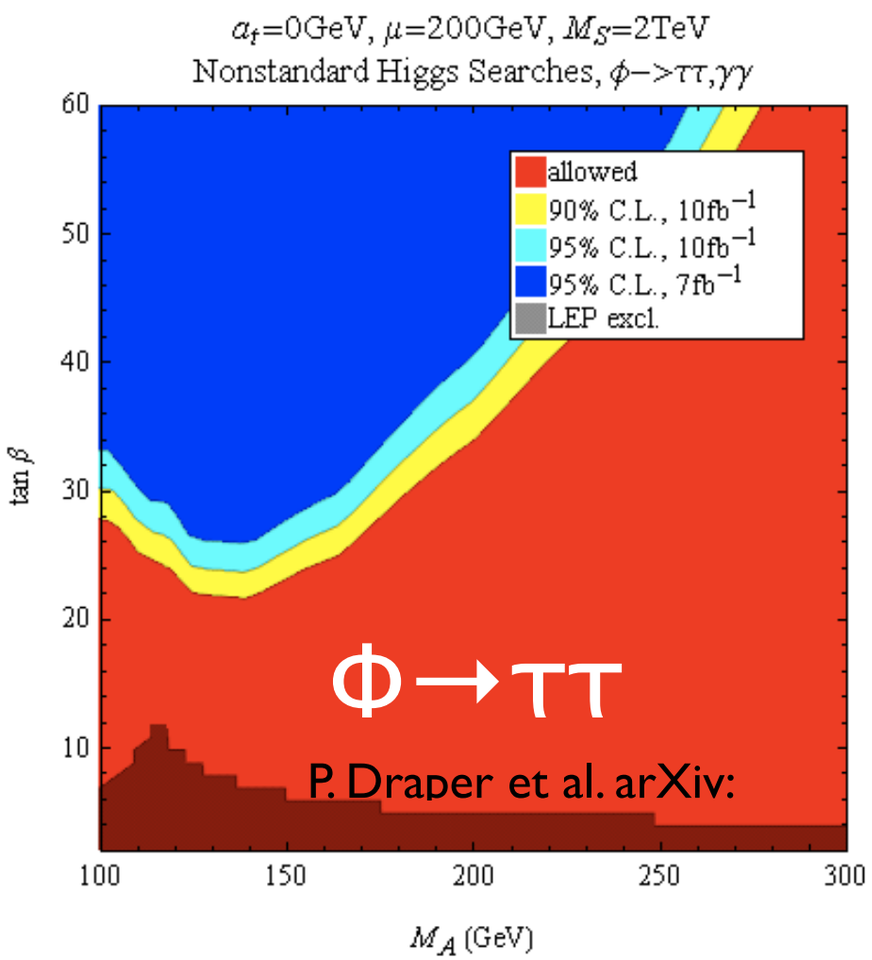
Including SM searches



+



Including SM searches



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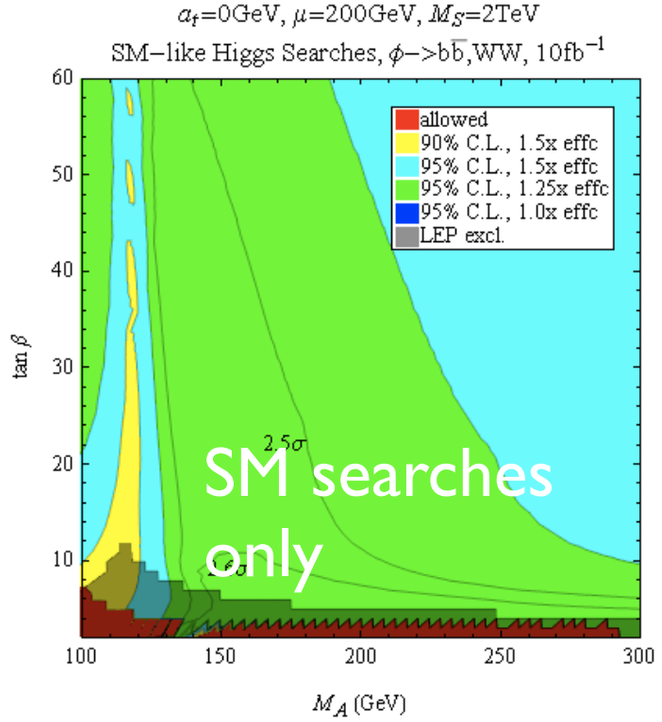
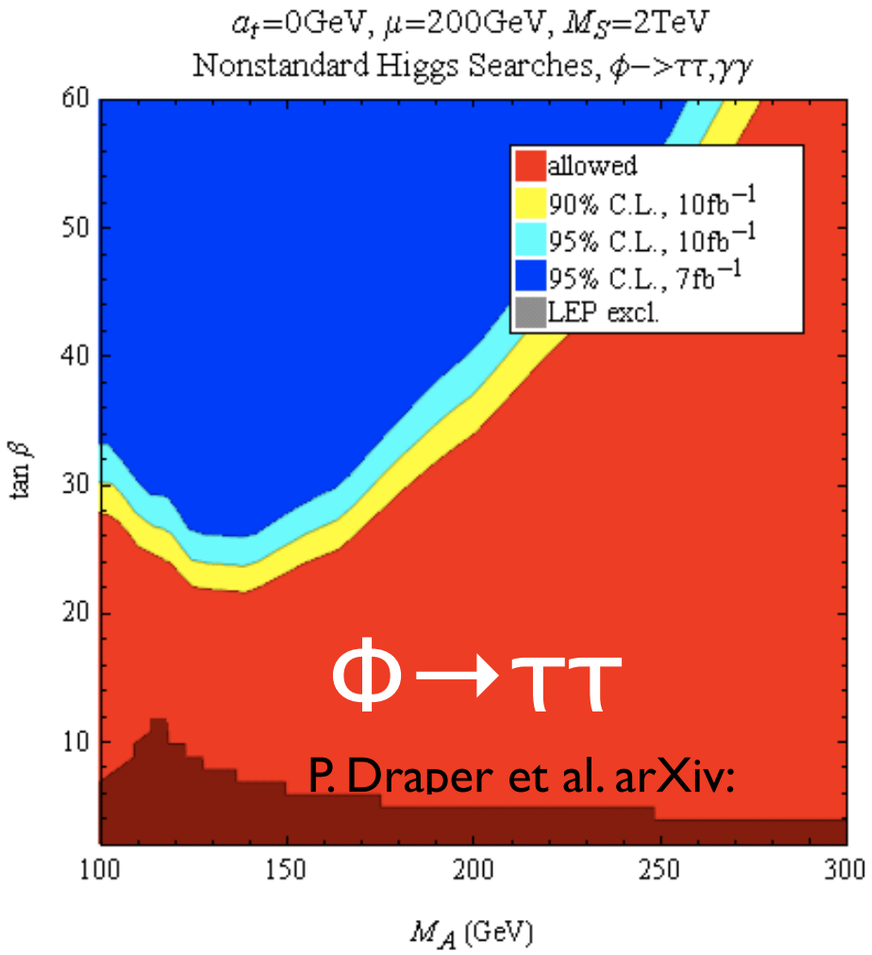
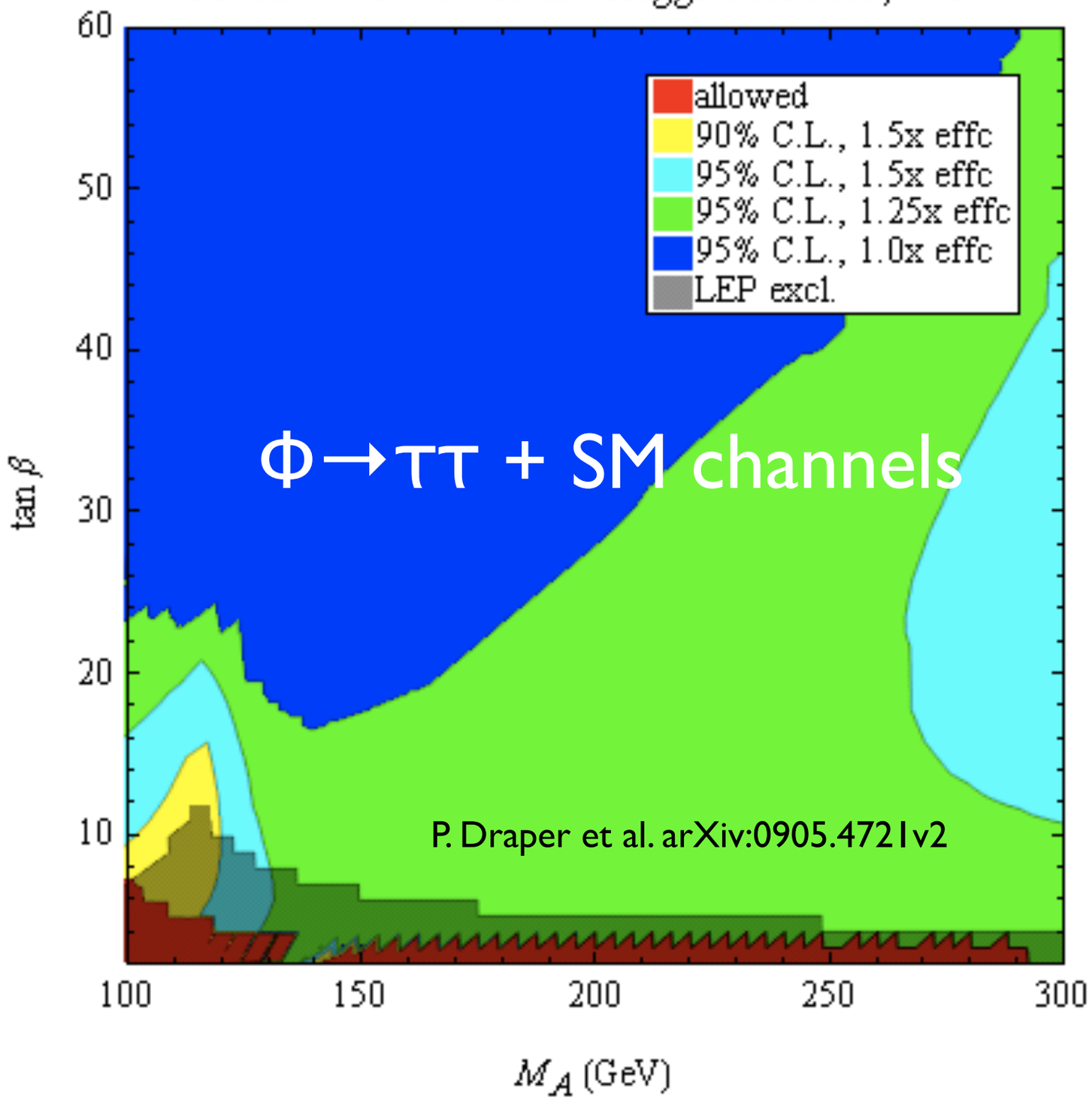


Including SM searches





Conclusions

- TeVatron is performing better than ever...

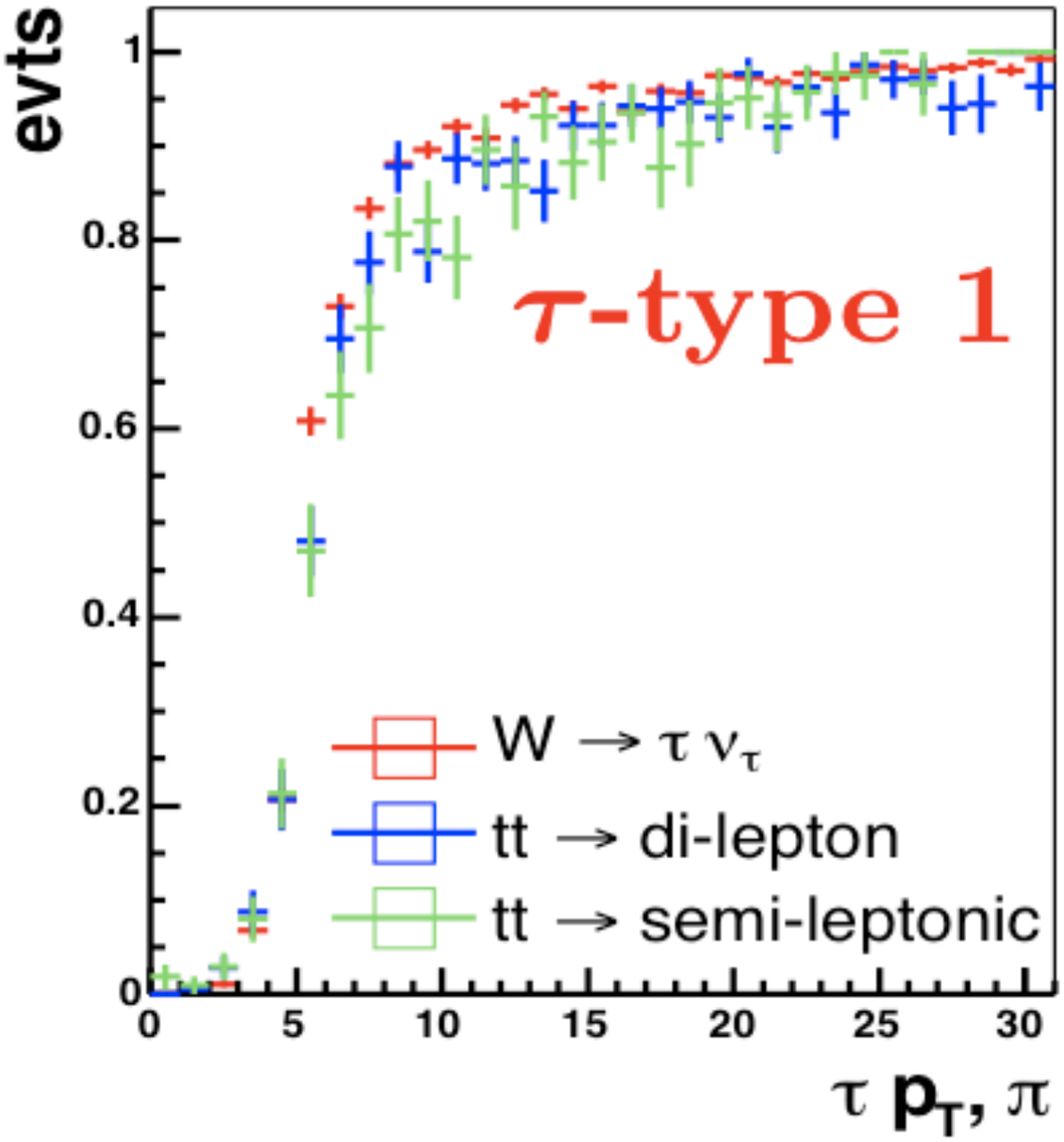
  Many thanks to the accelerator division

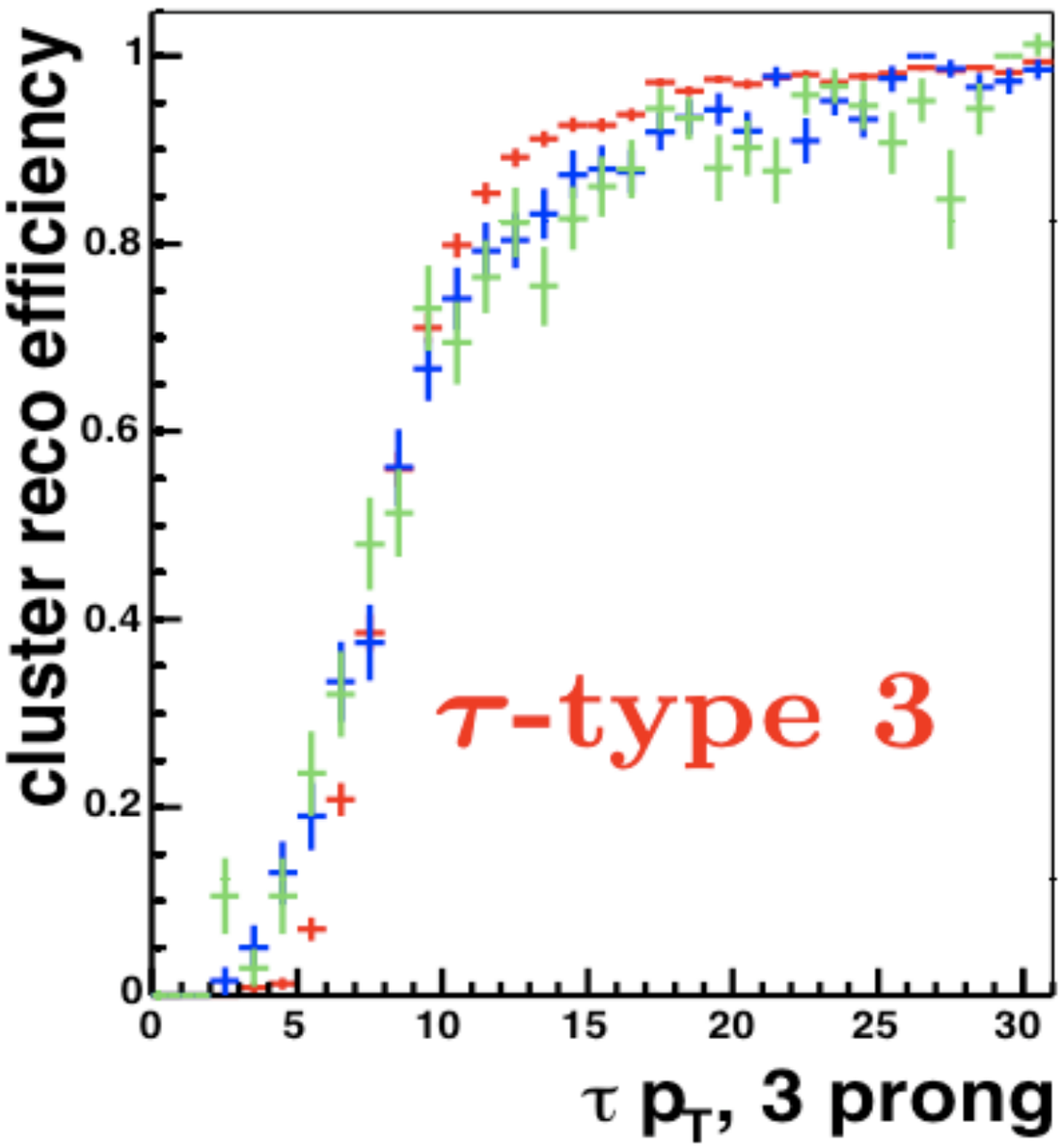
- DØ is tracking down MSSM Higgs bosons in every corners of the available phase space:
  - $\Phi \rightarrow \tau\tau$
  - $b\Phi \rightarrow bbb$
  - $b\Phi \rightarrow b\tau\tau$
  - $t \rightarrow b\, H^+$
  - and more, NMSSM...
- Combination tools in place: benefit from the complementarity of the different channels
- Results shown today use only a subset of the total available luminosity so far but already probing an interesting part of the MSSM phase space... Much more to statistics to add.
- Including the SM searches should bring some more sensitivity.

Stay tuned!

backup

tau reco efficiency





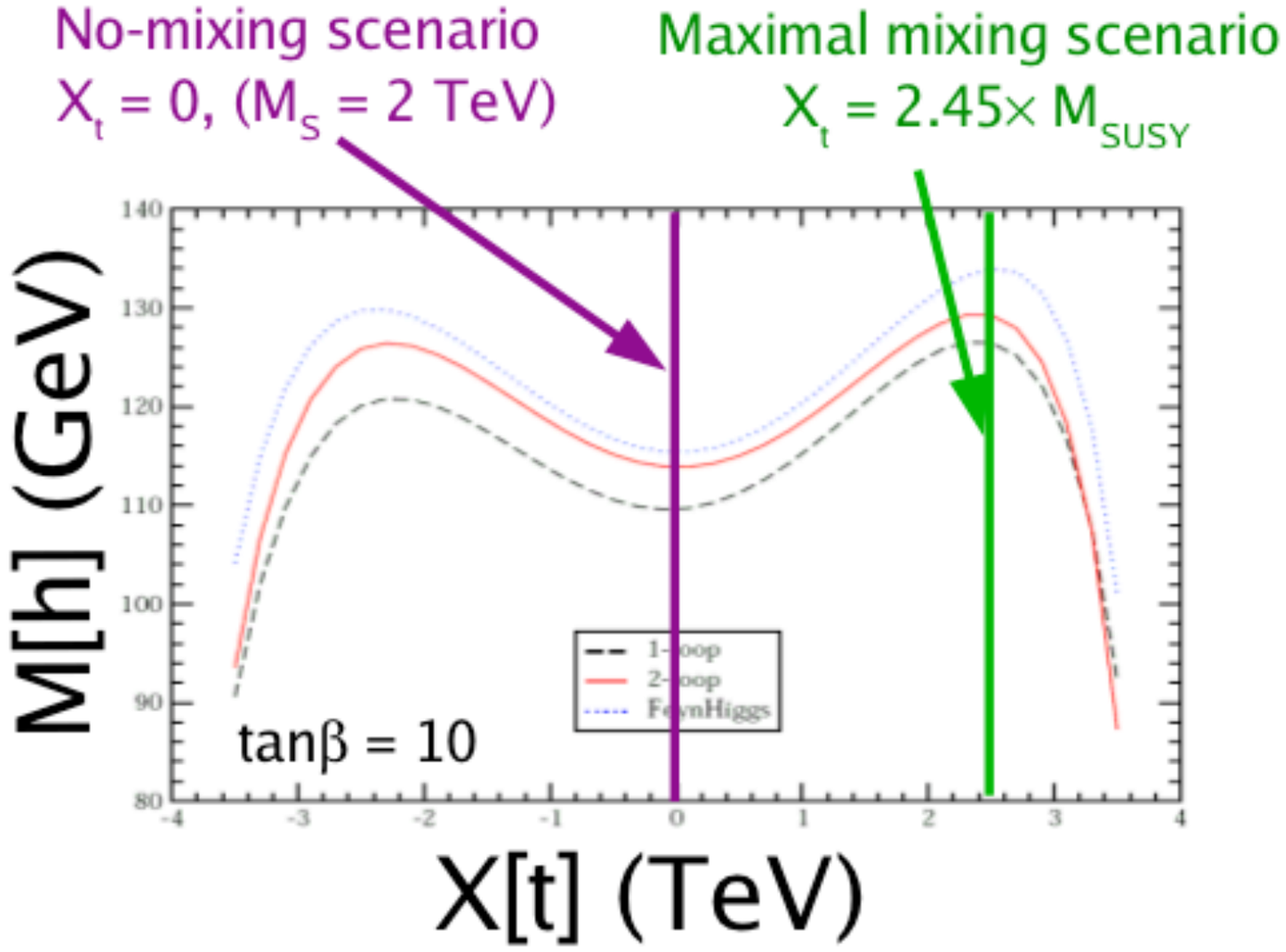
Maximal vs no-mixing

Common set of parameters

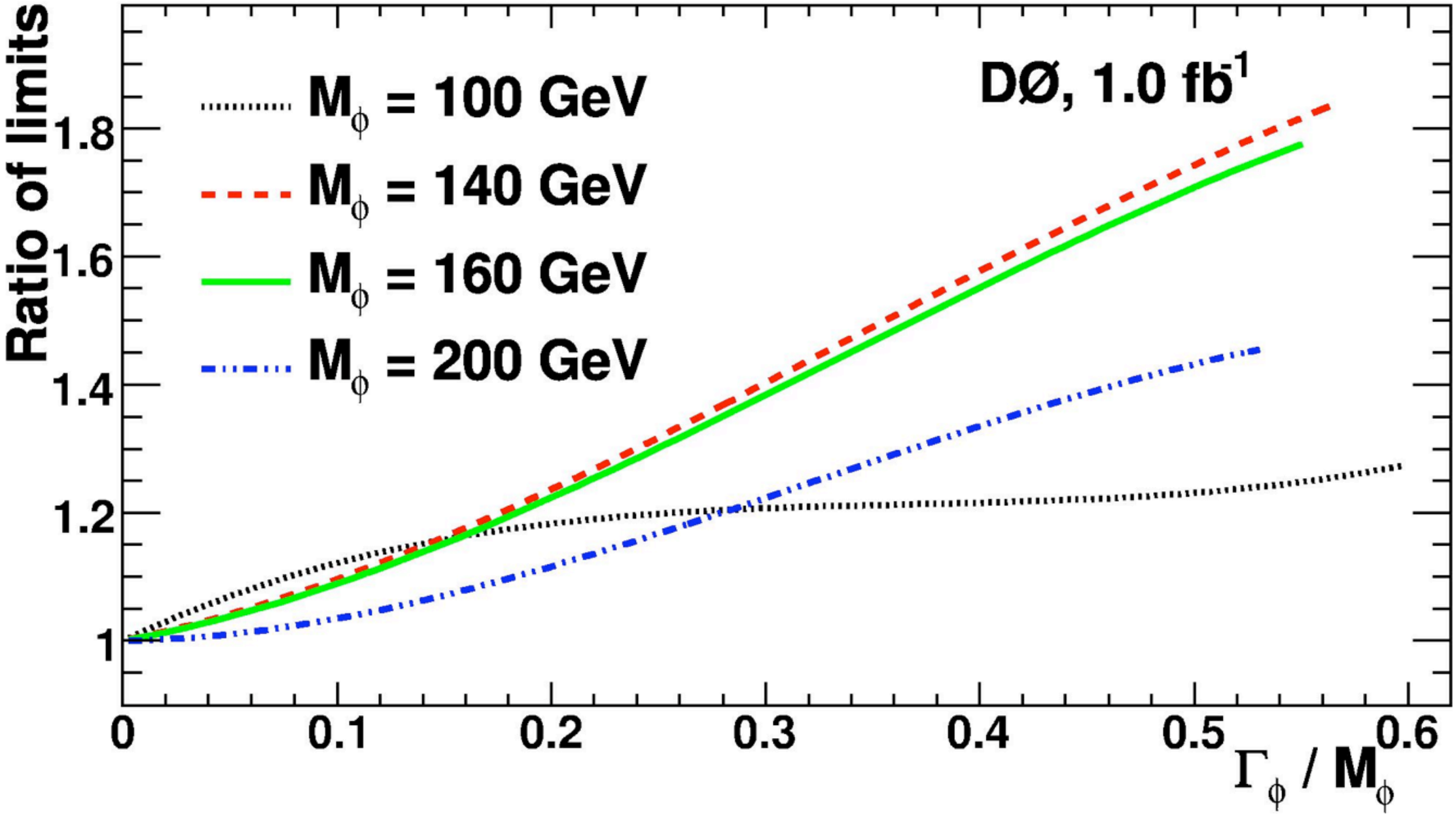
$$
\begin{aligned}
m_t &= 174.3\ \text{GeV}, \\
M_{\text{SUSY}} &= 1000\ \text{GeV}, \\
\mu &= -200\ \text{GeV}, \\
M_2 &= 200\ \text{GeV}, \\
A_b &= A_t, \\
m_{\tilde{g}} &= 0.8\, M_{\text{SUSY}}\ .
\end{aligned}
$$

sign of μ is varied

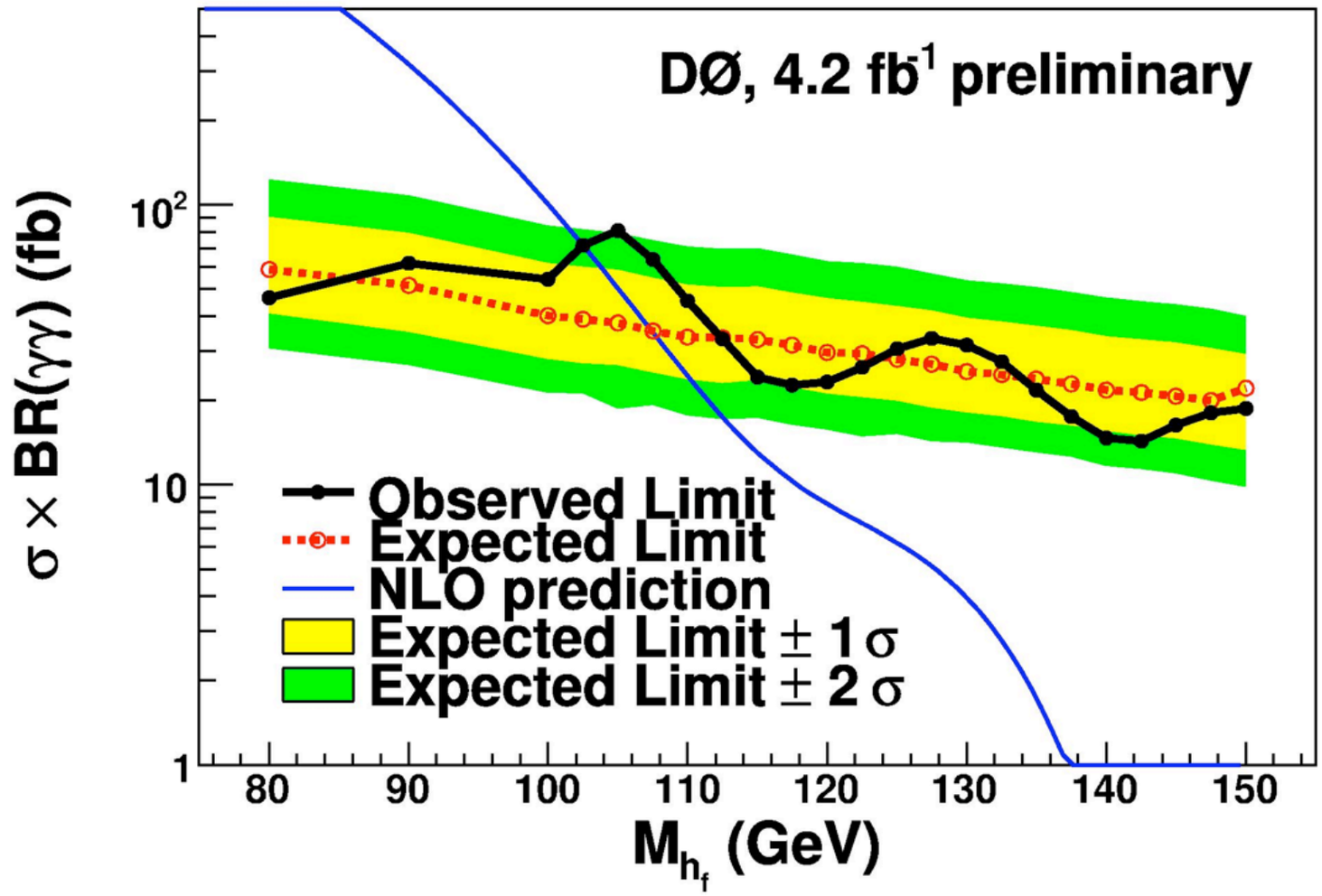
Differences in the stop mixing parameter X_t

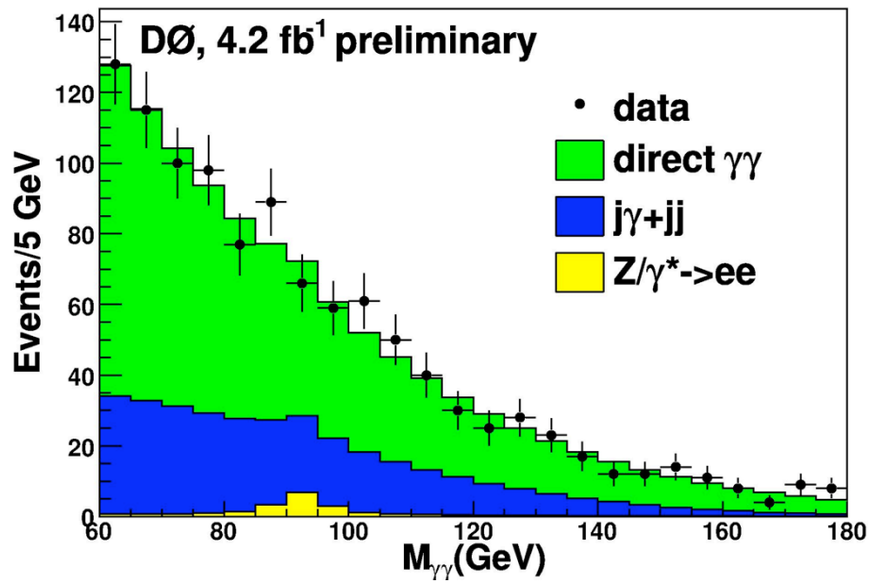


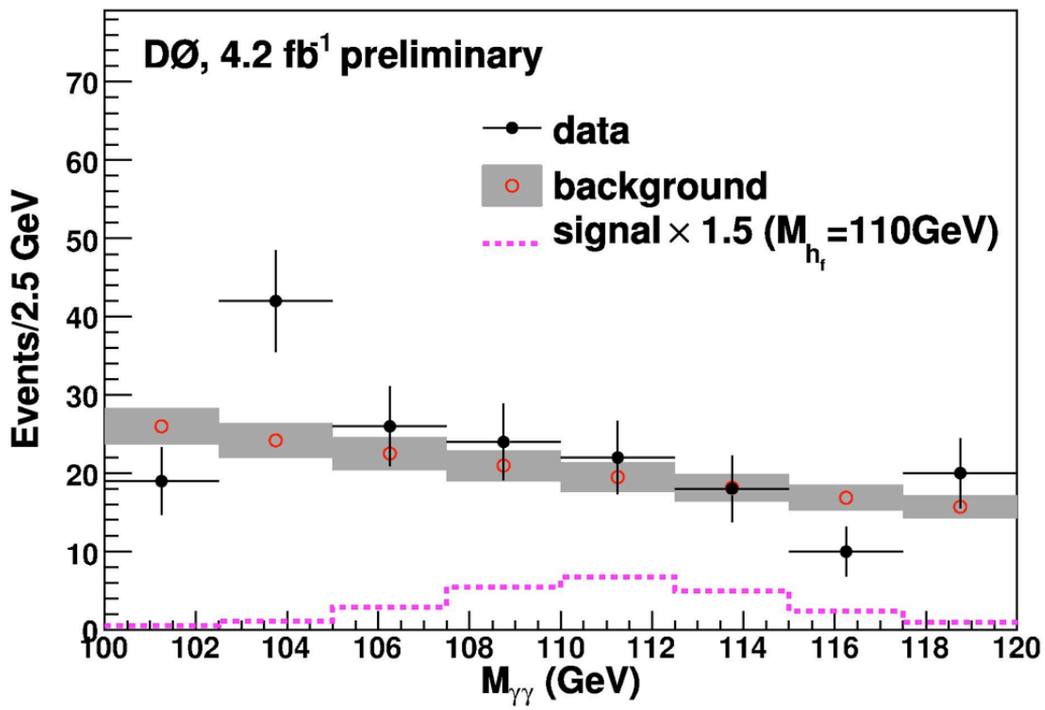
Φ width effect in τ τ



$h \to \gamma\ \gamma$







SM exclusion